84TH CONGRESS, 1ST SESSION, HOUSE DOCUMENT NO. 32

The Yearbook of Agriculture

1955

THE

YEARBOOK

OF

AGRICULTURE

1955

WATER

THE

UNITED STATES

DEPARTMENT

OF

AGRICULTURE

FOR SALE BY THE SUPERINTENDENT OF DOCUMENTS,

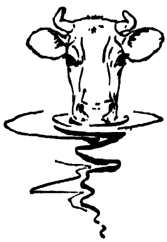
WASHINGTON 25, D. C.

PRICE $2.00

THE UNITED STATES GOVERNMENT PRINTING OFFICE

Foreword

Ezra Taft Benson,
Secretary of Agriculture



I have little need to remind you that water has become one of our major national concerns.

Nearly everyone in this country in the past few years has experienced some problem caused by too much water when we do not want it or too little water when we do want it.

Farmers have had to haul water for stock in trucks from cities. Some cities have had to haul water from farm ponds. New Yorkers for a time were asked to cut down the number of their baths, so low was the water in the reservoirs that serve the metropolis. Homeowners in many places had to give up watering their lawns in order to husband municipal supplies. Some city councils have had warnings that the growth of their cities would be limited by the availability of water. An ample amount of clean water has become a factor in the location of new factories. The intrusion of salt water into overused wells is making unusable the water in some underground reservoirs.

Farmers know only too well the difficulties that attend getting enough water for irrigation, the need for supplemental irrigation, the hazards of pollution, and the deficiencies of good water for house, stock, gardens, and crops. They have known the worries of dry wells, failing springs, and erratic surface supplies. They have suffered the fury of floods and the worries of erosion. Losses in life, security, productivity, and money have been great.

Those problems and many more like them you know. What have we done about them? What more can we do to solve them?

We have to know where water comes from and what happens to it. We have to know how much can be used and when, and how our land practices influence its behavior.

We have to stop wasting water. We have to use it more efficiently in industry, in towns and cities, in general farming, and in irrigation, which is destined to be adopted in all parts of the Nation.

We have to learn more about the control of floods at their sources as well as in the big rivers. That will take county, regional, and national planning—much more planning for the future than we have ever done.

We have to look to the fields, the forests, and the hills that make up our watersheds, for the way we manage them affects the abundance and purity of the water farmers and city people need in increasing quantities.

We need to explore all possibilities that the sciences now offer—"cloud seeding," forecasting water supplies, converting saline waters, treating waste water, reducing erosion and floods, cutting down evaporation, finding out more about how plants use water, and many more.

We need an increased awareness among all Americans of the oneness of our physical resources. Just as many lives make up our one national life, so our agriculture has many parts of a single whole. Water, land, and people are inseparable components of one thing, our welfare. The subject of water can be viewed from the various aspects of soil conservation, agronomy, forestry, irrigation, wildlife, recreation, business, industry, law, and so on—but never alone.

We are making encouraging progress toward the fulfillment of those needs.

The 83d Congress enacted the Watershed Protection and Flood Prevention Act, which established permanent legislative machinery under which the Federal Government can cooperate with local organizations, including the States, in planning and carrying out works of improvement for flood prevention and the agricultural phases of the conservation, development, utilization, and disposal of water on small watersheds.

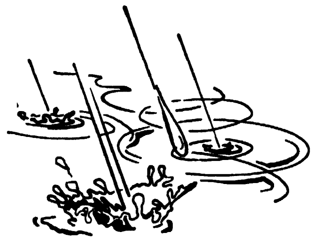
The Congress also amended the Water Facilities Act so that long-term loans can be made in all of the States for water and soil conservation practices, irrigation, drainage, the establishment of improved pastures, and reforestation. Other legislation promotes the adoption or improvement of sound conservation practices on crops, pasture, range, and forest lands.

In other places and by other persons the problems are being tackled practically and forthrightly—by industry, suburban communities, municipalities, research workers in State and Federal agencies and universities, and farmers.

The new watershed protection program clearly should not be looked upon as some miracle coming out of the Federal Treasury. If it is successful, it will be because local people, working through their local organizations with the help of their State Governments, are determined to assume and maintain the principal initiative and bear a major share of the cost of the job, seeking from the Federal Government only that additional assistance which is beyond their technical and financial capabilities. We cannot separate people and program in this important work.

Preface

Alfred Stefferud,
Editor



There's a lot to be known about water.

We see and feel rain, snow, dew, fog. We use water for drinking and washing. We irrigate our lawns and fields. We talk about the weather, complain that it is too wet or too dry, and misquote Mark Twain about it. Most of us are conscious nearly all the time of the importance of water in our lives, but actually our knowledge of it is pretty skimpy.

We know the symbol of water but little about its properties, which can make us comfortable or uncomfortable, rich or poor, secure or insecure. We cannot live without water; we could live better if we knew more about it.

One purpose of this Yearbook is to supply as much information as we can about water in a practical, useful way for farmers and others who use water. But not only that.

Another aim is to emphasize that more information, more wisdom are needed. That need is mentioned again and again in the book; a whole chapter, in fact, is devoted to it. The realization of ignorance is the beginning of wisdom. The statement of a problem is the first step in its solution. It is a duty to discover facts in a true scientific, unbiased, unselfish spirit—a duty for us who prepared the book and, I submit, for those who read it.

The committee that planned the scope of the book set forth this aim at the start for the guidance of the men who wrote the chapters:

"Our primary aim is to explain the nature, behavior, and conservation of water in agriculture. We address ourselves to farm people and to all those interested in rural living. As our population increases, more demands are being made on our water resources; the effective use and conservation of water on farms will become increasingly important, and conflicts over water use will have to be resolved. Some of the broad problems are forecast, but our main emphasis is on the facts and basic principles that will help people in reaching the best decisions. Hydroelectric

power, navigation, industrial use, pollution, and other aspects are touched on, but this book is concerned almost entirely with water in agriculture."

The members of the Yearbook Committee for 1955 are:

Agricultural Research Service: Carleton P. Barnes, Elco L. Greenshields, Omer J. Kelley.

Forest Service: Bernard Frank, Warren T. Murphy, Dana Parkinson.

Soil Conservation Service: Carl B. Brown, Charles E. Kellogg, George R. Phillips, Gladwin E. Young.

Office of Information: Alfred Stefferud.

Our hope is that you will read the book again 5 years from now, 10 years from now, 25 years from now. The information it contains is not just for today. All things, including weather and rainfall, change fast, and our memories are short. When it rains, we forget about the dust bowl; when it is dry, we forget about floods.

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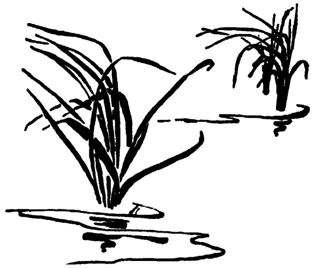

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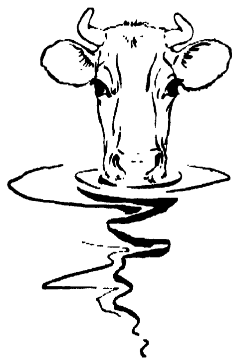

Our Need For Water

The Story of Water as the Story of Man

Bernard Frank

You could write the story of man's growth in terms of his epic concerns with water.

Through the ages people have elected or have been compelled to settle in regions where water was deficient in amount, inferior in quality, or erratic in behavior. Only when supplies failed or were made useless by unbearable silt or pollution or when floods swept everything before them were centers of habitation abandoned. But often the causes lay as much in the acts or failures of men themselves as in the caprices of Nature. So, too, man's endeavors to achieve a more desirable relationship with the waters of the earth have helped mold his character and his outlook toward the world around him.

People always have preferred to meet their water troubles head-on rather than quit their places of abode and industry. So people have applied their creative imagination, and utilized their skills, and released heroic energy. The ancient wells, aqueducts, and reservoirs of the Old World, some still serviceable after thousands of years, attest to the capacity for constructive thinking and cooperative ventures, which had a part in human advancement.

Fifty centuries ago the Mohan-Jo-Daro civilization of the Indus Valley in India enjoyed the benefits of well-designed water supply and drainage systems and even public swimming pools and baths. Excavated ruins of that period have revealed a surprising variety of waterworks, including tanks and irrigation canals.

The people of Assyria, Babylonia, Egypt, Israel, Greece, Rome, and China built similar facilities long before the Christian era. Egypt has the world's oldest known dam, a rock-fill structure built 5,000 years ago to store drinking and irrigation water and perhaps also to hold back floodwaters. Its length was 355 feet, and its crest was 40 feet above the riverbed. Apparently it was poorly designed, for it failed soon after, and no other was erected for 3,000 years afterward. Jacob's well was excavated through rock to a depth of 105 feet. The well is reported to be still in use. About 950 B. C., Solomon directed the construction of sizable aqueducts to provide for the needs of man, beast, and field. Ancient Arabia's enterprising farmers utilized extinct volcanic craters to store surface flows for irrigation and drove deep wells to get drinking water. Babylonia's King Hammurabi supervised the digging of an extensive network of irrigation canals and promulgated laws for their repair.

Among the early Greeks, Hippocrates recognized the dangers to health of

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polluted drinking water and recommended that water be filtered and boiled. The Romans used their poorer waters for irrigation and fountains.

The Tukiangyien system, built in China some 2,200 years ago, is another tribute to the genius and toil of ancient peoples. This skillfully designed multipurpose engineering project was intended to divert the flows of the Min River, a tumultuous stream that rises on the high plateau of Tibet. By building a series of dams and dikes on the main river where it first enters the broad plain from the mountain canyon, the farmers divided its flow into many parts so they could irrigate one-half million fertile acres. The structures—composed of bamboo frames weighted down by rocks—also reduced greatly the heavy toll of life and property from spring and summer floods.

THE HABITS OF MEN and the forms of their social organizations have been influenced more by their close association with water than with the land by which they earned their bread. This association is reflected in the Psalms of the Hebrew poets and in the laws, regulations, and beliefs among the civilizations of the Near East, the Far East, and South America.

Read, in the Old Testament: ". . . A good land, a land of brooks of water, of fountains and depths that spring out of valleys and hills . . ." (Deuteronomy 8: 7). "I did know thee in the wilderness, in the land of great drought." (Hosea 13: 5). "Drought and heat consume the snow waters . . ." (Job 24: 19). "He sendeth the springs into the valleys, which run among the hills. They give drink to every beast of the field: the wild asses quench their thirst. By them shall the fowls of the heaven have their habitation, which sing among the branches. He watereth the hills from his chambers . . . He causeth the grass to grow for the cattle, and herb for the service of man . . ." (Psalm 104: 10–14).

Property in water long antedated property in land in the arid lands of antiquity. Property rights were associated primarily with the uses of water—first for drinking, next for irrigation. Mohammed saw water as an object of religious charity. He declared that free access to water was the right of every Moslem community and that no Moslem should want for it. The precept of the Holy Koran, "No one can refuse surplus water without sinning against Allah and against Man," was the cornerstone of a whole body of social traditions and of regulations governing the ownership, use, and protection of water supplies.

All persons who shared rights to a watercourse were held responsible for its maintenance and cleaning. The whole community was responsible for the care of large watercourses. Cleaning was to start at the head of the stream or canal, descending in order to each waterside family. All users shared the cost in proportion to their irrigation rights.

Even marriage might be influenced by the difficulties of obtaining water. The inhabitants of one rural community in southeastern Asia must walk 9 miles to the nearest sources of drinking water—a group of wells. Local custom decrees that wives must fetch the water. One wife can make only one trip a day with her bucket—not enough for the family's needs—and so a man finds it desirable to have several wives.

ALL LIFE DEPENDS ON WATER. For us today water is as necessary for life and health as it was for our prehistoric ancestors. Like air, water is bound up with man's evolution—and doubtless his destiny—in countless ways. One of the basic conditions for life on earth is that water be available in liquid form.

The origin of all life on our planet is believed to be the sea, and today, after millions of years of evolution, modern man's tissues are still bathed in a saline solution closely akin to that of the sea when the earlier forms of life first left it to dwell on the land.

Every organic process can occur only in the watery medium. The embryo

floats in a liquid from conception to birth. Breathing, digestion, glandular activities, heat dissipation, and secretion can be performed only in the presence of watery solutions. Water acts as a lubricant, helps protect certain tissues from external injury, and gives flexibility to the muscles, tendons, cartilage, and bones.

The role of water in metabolism, in regulating body temperature, and in nourishing the tissues, explains why we could not long survive without adequate amounts of water. Yet our direct bodily needs for water are relatively small in terms of our total body weight (itself more than 71 percent water) and infinitesimal in relation to the total demands upon water by human societies, even among primitive cultures.

The average person in the Temperate Zone can get along with about 5.5 pints of water a day if he is moderately active. Slightly more than 2 pints are taken in with a normal mixed diet or created in the body by the oxidation of food, especially sugars, starches, and fats. Another 3 pints are taken in as fluids. Altogether it takes 5 or 6 pints to replace the daily losses in perspiration, exhalation, and excretion.

The amount for a given individual varies with his weight, age, activity, health, and other factors, but basic needs must be satisfied if life is to go on. The consumption of lesser amounts than those needed to replace losses will lead to a diminished appetite and eventually to undernutrition. A man in good health might be able to survive without water for a few days in a desert if he is only slightly active. If he tried to be more active he might not last a single day, because the consequent losses of water—as much as 10 pints an hour—from the body would greatly exceed the losses incurred under slight activity. Unless water were promptly made available, the losses would cause dehydration, incapacity, and painful death. By contrast, in the parts of the Tropics where high temperature and high humidity prevail, high rates of activity cannot be maintained even if abundant water were available, since the body is unable to dissipate heat and rid itself of waste products fast enough to prevent a breakdown in body functions.

WATER SERVES in many other ways to maintain life, health, vigor, and social stability. The nutritive value of food crops may be affected by the amount of moisture available to them when they are in active growth. Because the minerals in the soil can be taken up by plants only when they are in solution, the amounts thus made available are greatest when the soil is moist.

The oceans, lakes, and flowing waters and their shores furnish food and clothing. Men always have looked to such places for a goodly part of their diet of proteins and carbohydrates. The gathering of fish, lobsters, crabs, and other crustacea, the waterfowl, fur bearers, and other wildlife that frequent riparian environments, and the stems, roots, bulbs, or fruits of bulrush, watercress, marshmarigold, water chinquapin, wildrice, and other water-loving vegetation have furnished sustenance to people the world over.

The occurrence of water in a locality confers advantages on the people who own or use the lands. The lakes, beaver ponds, the waterfalls, cascades, bogs, swamps, springs, or snowfields that feature wilderness, park, and the other recreational places and the colorful plants and wildlife that thrive there provide an appeal that attracts many people to the outdoors.

NATURAL WATERWAYS—oceans, lakes, and rivers—have greatly facilitated the worldwide spread of population and of commerce. Most of the permanent settlements in the arid regions—today as in antiquity—have concentrated along river valleys. Even along the seacoasts, habitation clustered around or near the convenient sources of fresh water.

The early Egyptians along the Nile and the Incas at Lake Titicaca in Peru employed rafts cleverly constructed of

native plants. Solid logs filled with double outriggers and platforms made seaworthy craft in Africa and Polynesia; later craft were constructed from logs hollowed out by fire and crude tools.

Inland transportation since early times has been facilitated by canals, first for irrigation and later for transport, as among the early Assyrians, Egyptians, and Chinese. The Grand Canal, built in China in the 13th century, served irrigation needs and also provided an important artery of commerce for the products of its millions of people. European countries, notably Holland, France, and England, later developed extensive systems of canals between natural waterways. So, too, in the Andes region of South America, rivers are the arteries on which rubber, lumber, and other products of the interior are carried to the coast.

Early settlement in the United States, at first restricted to the coastal strips, soon moved westward through the mountains by utilizing such streams as the Mohawk River in New York, the upper Potomac in Maryland and West Virginia, and the Ohio. By 1790, shortly after our country achieved independence, all but 5 percent of the 4 million inhabitants still lived along the Atlantic seaboard, but the way westward was rapidly being charted. River craft had navigated up the coastal rivers to the fall line. Canals to bypass the unnavigable parts of rivers were already built in Pennsylvania—connecting the town of Reading on the Schuylkill River with Middletown on the Susquehanna—and around the rapids at Harpers Ferry, W. Va., on the Potomac. Following the successful tests of steam-propelled craft, large fleets began to haul wheat, coal, and iron on the Ohio River, the Great Lakes, and the Mississippi.

As the country expanded and prospered, eyes turned increasingly to the opportunities on the major rivers. Today, notwithstanding the intensive networks of railroads, highways, and airways, our improved navigation waterways—developed largely by the Corps of Engineers—total more than 25,000 miles and in 1953 carried a volume of raw and manufactured products amounting to nearly 225 million tons. It is possible to travel by boat from the Gulf of Mexico to Sioux City, Iowa, a distance of 2,030 miles.

MODERN CIVILIZATION imposes heavy demands on water. Merely to sustain life takes relatively little water. But even in pastoral or other simple societies, additional amounts are needed in preparing food and washing our bodies and clothes. The total daily requirement for all purposes, including drinking, in ancient villages may have averaged 3 to 5 gallons a person. Now a person uses 60 gallons or more each day for household and lawn-watering purposes in the average electrified farm or urban home in the United States! The figures are for homes with running water; the corresponding average for homes without that convenience is only 10 gallons a person a day.

At the minimum comfort level of 5 gallons a day—corresponding to the needs of primitive living conditions—our country's 165 million people would have few serious water difficulties. That daily total consumption of 825 millions of gallons would represent 0.07 percent of the Nation's average daily runoff of 1,160 billion gallons a day and 1.2 percent of the amount used up (not available for reuse) in the United States.

But our technological civilization could not have been attained at a level of water consumption geared to the requirements of primitive societies, even in our humid sections, where the need for irrigating crops is relatively slight. The steady rise in the consumption of water in industrially advanced countries explains why we now regard our water supplies with great concern.

The impact of new inventions and new developments and growth in population and industry has not commonly been given the attention it has merited.

Many critical local water shortages

therefore have occurred that could have been forestalled. For example, rural electrification has brought about such heavy increases in the use of water for household and production purposes that the limited well-water supplies of many farms have been severely strained.

Similarly, factories have been built without prior studies to determine whether water would be available to operate the factories and to provide for the communities around them.

Towns, cities, industries, and farms have kept expanding beyond the safe limits of available water. Often makeshift efforts have been necessary to meet emergencies, especially in years of low rainfall. Such efforts have often hastened the depletion of the limited reserves in underground reservoirs, generated disputes with other cities or industries drawing on the same sources of water, introduced conflicts with the use of water for recreation, and threatened the permanent flooding of lands valuable for farming, forestry, wilderness, or wildlife.

To meet the difficulties, more thought is being given to the advance planning of storage reservoirs, aqueducts, canals, methods of recharging ground water, reclamation of waste waters, and other devices. Still the search for more and better water goes on. Use continues to rise; advancing standards of health and comfort, the application of more intensive farming practices, and the development of new products all impose additional demands. In fact, the proportion of our total economic and recreational activity—both in rural and urban areas—that depends on handy and abundant supplies of clean, safe water is greater than ever before in our history.

OUR WATER NEEDS are indeed great. Yet they do not begin to compare with the needs of the millions of people in Asia Minor, India, Africa, and South America who must still scoop up water from shallow pools or foul streams or haul it up by hand from wells. Travelers relate how in Madagascar the women carry water home in jars on their heads across miles of hot sands. In parts of the Egyptian Sudan, water is stored in the trunks of large, hollow trees. The openings are sealed with wet clay to keep it uncontaminated. Thousands of these small reservoirs—which hold 300 to 1,000 gallons each—appear along routes of travel. In one province all the trees are registered and the contents noted for information on the extent of the water resource.

Among the early pioneers, especially in the southern Appalachian Mountains, the ownership and control of a clean, abundantly flowing spring was considered an indispensable prerequisite to staking out a homestead. Once chosen, the spring was cherished. It meant cleanliness, health, and comfort. It was sheltered against contamination and protected against trespassers.

How far have most of us strayed from the old family spring! Generations of men and women have grown up without experiencing the joy of satisfying their thirst from cool, sparkling, spring water. Modern living standards have made it necessary to rely upon water supplies of far greater volumes than the one-family—or even the community—spring could furnish. Many of us have lost contact with the land and the pure waters that came from its depths. We must get water from distant rivers or reservoirs and then only after it has been made safe by filtration and chemicals.

THE TASK OF FINDING, developing, and maintaining suitable water supplies has not been limited to modern times. It has had to be faced wherever large numbers of people have crowded together in small spaces.

Paul B. Sears, discussing climate and civilization (in the book *Climatic Change*, edited by Harlow Shapley), wrote that the highly developed civilization of Babylon finally disintegrated because "for centuries the operation of agriculture had been increasingly burdened by heavy loads of silt in the life-giving [irrigation] canals." He added: "So

much labor was required for their annual cleaning that little leisure remained for anything else, and the long piles of silt . . . grew steadily in height and volume. Presumably this was due to increasing pressure, through cutting and grazing, upon the vegetation of the highlands whose runoff supplied the water. Under those conditions, the landscape became increasingly vulnerable to the effects of climate with its infrequent but violent rains and dry-season winds."

During the several centuries of stability under the Roman Empire, vast and intricate systems of waterworks had been constructed to provide the millions of people with safe supplies. Disposal of sewage was well developed for the times, and, in general, the value of clean household water and of sanitation was well understood. But when the empire disintegrated, chaos reigned, and the hard-won gains were rapidly dissipated. The constant warfare and political disturbances broke down the social concerns over water supplies, among other important public services. As ignorance and poverty increased, sanitary precautions came to mean less and less, and in time cleanliness was frowned upon as evidence of wicked thoughts and self-indulgence. Bathing, formerly widely practiced for its therapeutic values, was abandoned. The citizens no longer took pride in clean homes and streets, which became filthier and filthier. Worst of all, the water, obtained mostly from wells, eventually became so fouled as to be unfit for use.

Illness and death from waterborne diseases have plagued one country after another down to the present time. And not only were the poor people struck down. Records indicate that many famous characters of history also fell victim to waterborne diseases. Among them was King Louis VIII of France, Charles X of Sweden, Prince Albert of England, his son Edward VII, and his grandson George V. George Washington was known to have suffered from dysentery. And Abigail Adams, wife of the second President of the United States; Zachary Taylor; and—ironically enough—Louis Pasteur's two daughters are said to have died of typhoid fever.

Apparently the popular indifference toward safe, clean water prevailed well into the 19th century, even in England and the United States, where the dangers from the polluted supplies were generally known.

The effects of polluted waters now are considered to be the foremost obstacle to raising the living standards of underdeveloped countries.

GREAT STRIDES have been made since 1900 toward meeting our needs for water—and we have been going farther and farther away to get it. Today, for example, Los Angeles obtains its water not only locally—from the Sierra Madre in southern California—but also from the Owens River on the east side of the Sierra Nevada, 240 miles away; Mono Lake, 350 miles away; and from the Colorado River, 450 miles away.

But the end is not yet. New sources of water are sought for the swelling population of southern California. Sewage, formerly discharged into the ocean, is reconditioned for irrigation and industrial use; eyes are turning to the better watered, less densely peopled northern part of the State; and the possibilities of converting sea water are being studied by scientists.

EACH ONE OF US is affected by the water problems now before us. L. K. Sillcox, a sanitary engineer, estimated that about one-quarter of our total population is up against actual water shortages or poor quality of water or both. Population has doubled since 1900, but the per capita use of water has quadrupled, mostly because of industrial and agricultural demands. The 17 Western States, with about 37 million people, use a daily average of 85 billion gallons (77 billion for irrigating arid farmlands alone) as against 80 billion gallons in the 31 Eastern

States with their 128 million people. Industrial water in the East amounts to 65 billion gallons, as against 3 billion in the West. Farm irrigation in the East has taken only 3 billion gallons, but this use is growing so fast, and its impact on other uses has become so heavy, that many States—South Carolina, Georgia, Minnesota, and Wisconsin, for example—are closely reexamining their water policies with a view to developing new and more adequate legislation on this problem.

Mr. Sillcox estimated the Nation's annual water supply bill at 3 billion dollars, of which the urbanites' share is 500 million dollars. Farmers spend 200 million dollars (mostly for irrigation water). Investments in reservoirs, aqueducts, and other works to use or control water already total about 50 billion dollars—as against an outlay of 32 billion dollars to build our railways. (During the next 50 years we can expect to see further such investments by private, State, and Federal interests of 75 to 100 billion dollars.)

What to do about industrial wastes is another urgent and perplexing question. The Public Health Service estimates that it would take 9 billion to 12 billion dollars to rid our rivers of pollution and another 12 billion to 15 billion dollars to keep them unpolluted.

A special case of pollution as it relates to human health concerns the protection of the municipal and rural water supplies from radioactive wastes.

The coming years will bring an increase in the use of radioactive materials in manufacturing, for the production of electric power, and for experimentation in medicine, agriculture, and industry. The operation of nuclear power reactors alone will produce a manifold increase over the amount of radiation released to the air.

Radioactive materials released into the air are deposited sooner or later on the surface of the earth, including streams and lakes. Much of the radiation is noninjurious, and most of that which enters municipal reservoirs or other surface waters is rendered harmless by the application of modern detection and treatment methods. Not yet known, however, are the longtime, cumulative effects on human beings of the very small amounts of harmful radiation that still remain in the water we drink after it has been treated.

Studies indicate that the water that comes from underground sources, such as deep wells, is much less susceptible to contamination by airborne materials than are the surface waters. Other researches indicate that the distillation methods of purifying water are effective in eliminating sources of harmful radiation, even in large amounts; perhaps the future may bring radically different ways of handling our water supplies. Perhaps the same watershed conditions that favor the slow movement of water through the soil into underground storage may prove to be highly desirable also in facilitating the natural purification of contaminated waters. If so, watershed management, especially in localities that represent sources of underground water recharge, will take on added significance by providing an important safeguard to the protection of human health.

A serious challenge to our ingenuity is how to convert to useful service the savage energies of runaway floodwaters. The rapid growth in population in new and settled localities, on the flood plains and hill lands, and the corresponding expansion in highways, airports, factories, and homes have aggravated the tendencies of rivers, streams, and brooks to break loose when rain comes or snow melts. Despite heavy expenditures for levees, dikes, reservoirs, and other devices for curbing overflows, the damages from floods average about 1.2 billion dollars a year, including the value of the soil lost from productive farms and the deposition of silt and debris in irrigation canals and reservoirs and on the farms and city streets.

We have to pool our efforts if we expect to apply appropriate and durable prescriptions for our water ills. Few

activities have so clearly brought out the interdependence of all individuals, communities, States, regions, and nations as have our harried concerns with this product of the heavens. How it moves over the land and whether it aids or harms us depend on its behavior during its return to sea and atmosphere. The behavior of water directly reflects the conditions and uses of the lands from which it drains. Since drainage basins are composed of many kinds of land in many kinds of ownerships, our efforts to ameliorate those traits of water that we consider harmful bring into play the deep-seated, although often submerged, instincts of cooperation inherent in all forms of life. In that sense, water, perhaps to a greater extent than any other resource, takes on social significance.

Planning for the maximum development of our water resources for the longtime benefit of all of our people, when properly conceived, can bind together individual and the community, farmer, and urbanite, as few other conservation activities can do. Conservation has received perhaps its greatest impetus since our dealings with soil, forests, wildlife, recreation, community betterment, and industrial development have come to be viewed in terms of their interrelationships with water. More and more people have become informed and interested in all these fields because our water troubles and our attempts to resolve them on the watershed lands and in the river channels have had a direct impact upon their personal, economic, social, or recreational affairs. Thus, farmers on the Rifle River watershed in Michigan, who once seemed indifferent to rebuilding their eroding land, now enthusiastically participate in a watershed improvement program because they became convinced that fishing on their local streams would thereby be greatly improved.

Similarly, indifference toward stream channels, as exemplified by their use as dumps for garbage and trash, are changing with the development of individual and group awareness of what clean waters mean for their well-being. Men, women, and boys and girls in hundreds of communities are studying, thinking, planning, and carrying out programs to restore the attractiveness and utility of their local watercourses. In so doing they are developing a positive appreciation of the meaning of harmonious living with their fellowmen and their natural environment. As these wholesome cooperative endeavors spread through the land, we Americans cannot help but become richer in mutual understanding, more secure in spirit, more united in purpose.

BERNARD FRANK *is assistant chief of the Division of Watershed Management Research of the Forest Service. He has written extensively on water-resources and watershed management.*

For further reading:

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Necessary, Convenient, Commonplace

Sterling B. Hendricks

For all life water is necessary. For many uses it is convenient. In much of its functioning it is commonplace.

But commonplace things often are the least appreciated and the hardest to understand. We pay great attention to the movement of water from place to place as vapor and clouds in the air, as rain on the soil, and then as streams back to the ocean. We know that water is the most abundant liquid on the earth. Always we use or fight its tendency to find its own level. In considering its uses and abundance and properties, however, we must keep in mind this main fact: Water is needed for life.

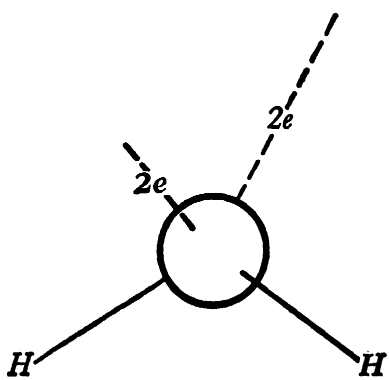
What is water? Why is it necessary?

The properties of water, such as the one that lets it float when it is in the form of ice, can be explained by the structure of its molecule, of which there are a trillion trillion in an ounce of water.

The molecules are formed of three elemental particles, or atoms, two of hydrogen (H) and one of oxygen (O)—or, expressed as a symbol, H_2O, which is one of the simplest compounds. The three atoms are held together by two chemical bonds, thus: H–O–H. Atoms consist of negative charges, or electrons (e), moving around a central positive nucleus. The number of electrons in an atom is the atomic number of the element in the periodic system of all the elements. Hydrogen is the first of the elements, and thus has one electron. Oxygen has eight. Chemical bonds are formed by pairs of electrons. The chemical bonds in H–O–H are formed by completion of two pairs, the electron of each H atom associating with each of two unpaired electrons from the oxygen atom. Of the remaining six electrons of oxygen, four are much farther from the nucleus than the other two are. The eight outer electrons in H_2O tend to form four pairs of electrons that are as far apart as they can be while still attracted to the oxygen nucleus. Thus they are near the corners of a tetrahedron, a solid bounded by four plane sides.

A further feature of a water molecule is that H attached to O is unsymmetrically surrounded by electrons, so that there is a separation of charge or polar character. If other molecules with nonbinding outer electrons are present, there is a tendency for H to increase the symmetry of its surroundings by approaching a pair of electrons in line with its chemical bond to oxygen, or 2e—H–O in a line. The resulting attraction, in case the 2e are on another water molecule, is about 6 percent as great as that of the H–O bond.

The properties of water arise from the hydrogen bonding and the tetrahedral arrangement of electron pairs around the oxygen atom.



In the diagram above of the water molecule, the dotted lines symbolize the hydrogen-bonding tendency arising from the diffuse cloud of electrons in the direction of the dotted lines. Several molecules held together by hydrogen bond, as in solid or liquid water, form an assembly of tetrahedral groups; each molecule is bonded to four other molecules, which it closely approaches.

The principles of bonding give the background required in explanation for the properties of water. The properties can be divided into two classes, depending on whether chemical bonds between the H and O atoms are broken in the action involved or whether only the hydrogen bonds are broken, leaving the H_2O molecules intact.

Chemical changes like the rusting of iron, the formation of clay in soils, or the splitting of cane sugar in the stomach are of the first class, in which chemical bonds are broken.

Physical changes, such as the melting of ice, evaporation in the boiler or from a lake, or the viscous resistance to flow in a pipe or stream, are of the second class. Most of the matters discussed in this book involve the properties having to do with the physical changes. They are the ones that man can manipulate. Life, however, depends upon both classes, for energy is derived from reactions in which chemical bonds are broken. Physical interaction is used for solvent action and the maintenance of structures, such as the structures of flesh or leaves, as can be seen by comparing a living creature with a mummy or fresh grass with hay.

A simple property, a physical one, to consider as a first subject is that water when heated evaporates very slowly as compared with other liquids that have simple molecules. In other words, the heat of vaporization is high. Vaporization is just the separation of molecules from a liquid or the overcoming of attraction between molecules. The high heat of vaporization is a direct result of the strength of the hydrogen bonding between molecules. In fact, since there are two hydrogen bonds in water for each molecule, the heat of vaporization is just about twice the hydrogen bond energy, 540 calories per gram (9,700 calories per gram molecular weight, or 4,850 calories per molecular number of hydrogen bonds).

Because of the high heat of evaporation, very little water is lost by evaporation in overhead irrigation. The evaporation that does take place, however, gives much cooling; a spray tower therefore is effective in cooling water if the relative humidity is low.

It is for that reason that a person sometimes feels chilly when he emerges from swimming. Dew is formed only when large quantities of heat are taken away; the dew that is formed, however, is slow to evaporate. The spread of some fungi and carriers of the plant diseases that require liquid water for growth are affected markedly.

A second result of the high heat of vaporization is that the boiling point of water is high. In other words, the molecules in the liquid have to move back and forth vigorously before they can spring loose into the vapor, the movement being a result of the increase in temperature. On the centrigrade scale, water at atmospheric pressure boils at $+100°$, the freezing point being $0°$, while oxygen (O_2) boils at $-183°$ and nitrogen (N_2) at $-196°$. Those differences are due chiefly to the hydrogen part in hydrogen bonding. Methane, CH_4, or natural gas, boils at $-161°$, even though it has the same weight per molecule as does H_2O. This low boiling point largely is due to the fact that all the outer electrons of the methane molecule are involved in chemical bonds only, with no free electron pairs available to participate in hydrogen bonding.

Water, then, is present as a liquid on the earth instead of just the gaseous form as are nitrogen and oxygen, the abundant constituents of the air. Several other planets that have greater masses (therefore, higher gravitational constants) than the Earth and are farther away from the sun (Saturn and Jupiter) have liquid methane and other hydrocarbon on their surfaces.

Life probably originated in liquid water and still depends upon it, even in the desert creatures that never drink. It is doubtful that life has originated in the seas of hydrocarbon on Jupiter.

Consider now as a further physical

property of great importance the fact that ice is lighter than water. Water is just about the only substance that has this property. It greatly affects man in cold and temperate climates by causing lakes to freeze downward from the surface instead of upward from the bottom. It results in the breakage of radiators and pipes, the heaving of the soil, and the gradual wearing down of mountains. It smooths the runners in skating, because of the drop in the melting point of ice with pressure, a consequence of the lower density of ice compared to water.

The explanation of the floating of ice, as well as for the high heat of fusion and the resistance to flow of water, depends upon the directional features of the hydrogen bonds, as shown in the earlier illustration. In ice at a low temperature, each water molecule is regularly surrounded at the four corners of a tetrahedron by other H_2O molecules. While the structure is firmly held together, it is a very open one in comparison with structures of most other substances in which each atom or group of atoms has 6 or more neighbors, the number being 12, for instance, for common metals for which the atoms are closely packed together, like fruit in a box.

When ice is heated from any low temperature to the melting point, the motion of the H_2O molecules is increased until they start to break the hydrogen bonds that keep them in the regular structure. When about 8 percent break loose and take up places in the voids of the tetrahedral array, the whole structure collapses a bit; the collapse causes melting, and the density increases about 9 percent.

As many hydrogen bonds have to be broken before melting takes place and the strength of each is quite great, the melting point (0°) and the heat required for melting (86 calories per gram) are relatively great. Water then freezes within the temperature ranges on the earth. In freezing it gives out heat to act against falling temperatures. That high heat for melting makes ice an excellent refrigerant; that and its convenience lead to its wide use in refrigerator cars.

Water is a cushion against both rising and falling temperatures, and therefore ameliorates the climate near oceans and large lakes.

Solids as well as liquids will flow. There are two chief requirements for such flow. First, the forces holding the molecules in place must be overcome. Second, there must be a hole in the structure into which the molecule can be moved. Water, then, with its high bonding energy between molecules, has a relatively high resistance to flow compared to other liquids such as gasoline and ether. The resistance limits the speed of boats as well as the rate of flow of water in a pipe or stream. A stream with a fixed gradient or head is limited by the resistance in the amount of water it can discharge.

Large bodies of ice with pressure from behind will flow slowly as solids in glaciers. In that ponderous way, the surface of the continent north of the Ohio and Missouri Rivers has been flattened and graded and the mountains of the West have been carved—the earth thus moved is millions of times more than all that has been moved by man since the beginning of time. Ice flows much more slowly than water because the number of holes into which the molecules can move after the hydrogen bonds are broken are very few and because fewer hydrogen bonds are being broken in a given time.

Water sticks firmly to itself, a property that we call cohesion. It also sticks to some surfaces; that is adhesion. The strengths of both cohesion and adhesion in water, of course, are due chiefly to hydrogen bonding.

First let us consider adhesion, the property of adherence to other substances. Water behaves quite differently on paraffin and glass. The wetting of glass—important in the action of a windshield wiper—arises from the formation of hydrogen bonds between the oxygen atoms, which are

part of the structure surface of the glass, and the hydrogen atoms of the H_2O molecules. Other substances that contain large numbers of oxygen atoms, such as clay and cellulose, are readily wetted in the same way. Thus cotton cloth, which consists of cellulose, absorbs perspiration, and clay suspends readily in water and causes streams to become muddy. But paraffin is not wetted because its fewer polar hydrogen atoms do not readily form hydrogen bonds. Nylon, which has some oxygen atoms, is intermediate between glass and paraffin in its tendency to wet. Therefore nylon can hold some water, but it still dries rapidly.

An example of cohesion—the tendency of water to stick to itself—is the floating of a needle on the surface of water. That you can do easily if you place the needle on the water so carefully that the surface of the water is not broken. In other words, a force is required to pull water apart and thereby to create two new surfaces. The force, in a sense, is opposed by a tension, and this surface tension of water is much higher than that of other liquids because of the hydrogen bonding.

From the surface tension of water it can be calculated that to rupture a column of water with a cross section of 1 square inch would take a force of about 210,000 pounds—which is a theoretical figure that cannot be reached because of the flaws in the water structure and the presence of dissolved gases, which give bubbles. But a practical limit of about 2,000 pounds a square inch, about 1 percent of the maximum, has been attained. The limiting tensile strength of water thus is about the same as that of some steels.

The ability of water to rise in small wettable tubes is important in the use of water by plants and the retention of water in soils. It is known as capillarity, or wick action. It depends on both cohesion in the liquid and adhesion to the walls. The height to which the liquid rises is determined by the surface tension and the weight of the column. The weight of the column depends on the cross section and the length of the column. The water in the column is under tension much as if it were a wire that is being pulled. The tension reduces the pressure of the vapor with which the surface is in equilibrium at a given temperature.

Water enters a tree through the roots and ascends through a series of small passages in the wood, to be lost by evaporation from the leaves. If the air at the upper surface of the water columns that end in the leaves has a relative humidity of 99 percent or less, a water column at least 430 feet in height (a tension of 200 pounds per square inch) can be supported. The sizes of the passages in the wood and the wettability of their walls are unimportant, but the water in the leaf must be in fine capillaries and the capillaries must have walls that wet. The equilibrium of the water with the vapor at the surfaces in these small capillaries supplies the tension that maintains the column.

Soils hold water in voids between particles, most of which have wettable walls. Capillarity functions in all the voids. It is most important in the small ones, where the liquid stays longest as drying takes place; that is, as the relative humidity in the soil drops because of withdrawal of water.

This holding of water by the soil against the force of gravity is a primary requirement in tilling the soil.

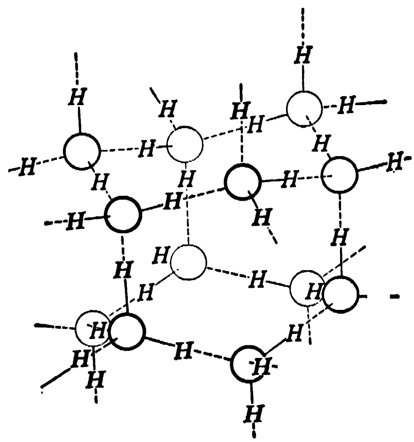
The solvent properties of water are the ones that make water so important in the life of plants and animals. The solvent action is of two types, in both of which water is outstanding among liquids.

One type depends on the hydrogen bonding. The other depends on separation of electric charge, or polar character in the sense of electrical poles. Sugars, alcohols, acetic acid and other organic acids, phosphates,

nitrates, ammonium compounds, and many other substances that have oxygen atoms, –O–H groups, or nitrogen bound to hydrogen atoms,

$$-N-H \text{ or } -N\begin{matrix}\diagup H \\ \diagdown H\end{matrix}$$

, are held in water solution by hydrogen bonding. They are the compounds involved in the storage and transfer of energy by the living plant or animal. They are the raw material for the production of other compounds, and they have to be transferred between parts of the living system. Water, by its hydrogen-bonding solvent action, is the medium of transfer in the fluid of blood or in the sap of plants.



Array of molecules

The polar dissolving action of water depends on the separation of the charge between the hydrogen and the oxygen atoms in H_2O molecules. Among the substances that are liquid at the usual temperatures, water has an unusually high separation of charge. By charge interaction, various salts are held in solution. Among them are sodium chloride, which man needs for the acid in his stomach and for the action of blood serum. Polar interaction also dissolves potassium salts, which are one of the three major components supplied in fertilizers and are involved in muscle action.

Finally we consider the chemical properties of water. They depend upon breaking of the bonds, H–O–H, between the hydrogen and oxygen atoms of the molecule. The molecules, being polar, have some separation of electric charge, and in the liquid the separation in a few molecules is so complete as to give two oppositely charged particles or ions, H^+ and OH^-. Here the hydrogen atom simply moves away, leaving its electron with the bonding pair of electrons on the oxygen atom and leaving the remaining part of the molecules (OH^-) with an extra negative charge. The H^+ is the hydrogen ion or the ion of acids and the OH^- is hydroxyl or the ion of bases such as lye. When carbon dioxide, CO_2, dissolves in water, it acts with these ions, thus:

$$CO_2 + HOH \rightleftarrows H^+ + HCO_3^-$$

That is the reaction of carbonated drinks. It also is of vital importance in keeping constant the acidity of blood and in holding carbon dioxide (formed by metabolism in the body) in solution to be delivered at the lungs. The chemical action of carbon dioxide and water dissolves limestone to form caves.

Many compounds can be split by water to form two compounds. Cane sugar, for example, is split into equal parts of glucose and fruit sugar (fructose), one water molecule being used up. Of greater importance in life, however, is the splitting of some phosphate compounds by water. The process releases energy, which can be used for building up other compounds.

$$\underset{\text{cane sugar}}{C_{12}H_{22}O_{11}} + HOH \rightarrow$$

$$\underset{\text{glucose}}{C_6H_{12}O_6} + \underset{\text{fructose}}{C_6H_{12}O_6}$$

Water has an essential part in photosynthesis, the process by which the energy of sunlight is gained for life—first the life of the plant and then (by the consumption of plants) for the life of animals. Sunlight on the green plant

causes oxygen to be evolved from water and causes the hydrogen atoms to be transferred eventually to carbon dioxide in such a way as to form sugar. The oxygen is used in metabolism by plants and animals to regenerate carbon dioxide.

Thus, water, oxygen, and carbon dioxide are in the closed cycle of life, with the essential hydrogen atoms shuffled back and forth and with sunlight driving the cycle.

STERLING B. HENDRICKS *has been doing research in the physical and biological sciences in the Department of Agriculture since 1928. In extensive investigations that continued from 1934 to 1944, he determined the structures of the minerals that form the clays and established one of the basic concepts of hydrogen bonding. In 1944 he began fundamental studies of plant nutrition and the effects of light on plant growth. He is a member of the National Academy of Science. In 1952 he received the Distinguished Service Award of the Department of Agriculture.*

Animals and Fowl and Water

Joseph F. Sykes

Water is closely linked with all the internal reactions in the animal body.

Water is necessary for the solution of food materials and waste products and their passage into and out of the tissues of the body.

The efficient transport of oxygen to the tissues and of carbon dioxide from the tissues to the lungs by the blood stream depends on a rapid flow of blood and on the maintenance of an adequate volume of blood, of which about 80 percent is water.

Water facilitates the various chemical reactions in the cells upon which vital activities depend and is an integral part of the colloid complexes of the tissues. Its physical properties make it an important factor in the transfer of heat in the body and in the regulation of temperature. An indication of its importance in those functions is the fact that the volume of water passing in and out of the blood stream in a minute is larger than the volume of water normally maintained in the fluid part of the blood stream.

Water is by far the most abundant ingredient of the animal body at every stage in development. The developing embryo may contain 90 percent of water. The body of the newborn calf contains 75 to 80 percent of water. The overall water content goes down, until at maturity 50 to 60 percent of the body of a lean animal consists of water. In very fat animals the water content may be no more than 40 percent. Apart from the fatty tissues, most of the soft tissues of the body are 70 to 90 percent water.

The concentration of water in the tissues is maintained normally at fairly constant levels. Severe restriction of water intake lowers the water content in tissues, and the blood becomes more concentrated. A concentrated blood means a failing circulation, an inefficient oxygen-carrier, and oxygen starvation of the tissues. Waste products tend to accumulate. Finally the vital activities are suspended, and death results.

Animals may lose nearly all the fat and about one-half the protein of the body and survive, but a loss of about one-tenth of the water from the body means death.

It is not surprising therefore that the highest development of the livestock industry usually has occurred in the temperate regions, most of which have a plentiful supply of rain. Not that the beneficial effects of temperate climates is due solely to the provision of water for animal consumption—adequate rainfall is also necessary for the production of feeds, pastures, and forages.

In hot, dry climates the untoward effects of less water for the livestock is

accentuated by the inadequacy of the feed supply for grazing animals. Actually, if an adequate forage supply could be provided for many of the semiarid ranges on which animals are maintained, the need for free water for animals would be reduced considerably. Many of the smaller desert mammals thrive for long periods without any visible source of water except that contained in dry seeds and the plants they consume. They do not seem to differ greatly from the larger domestic animals in their need for water or in their water-conservation mechanisms, except that they are able to protect themselves better against the effects of the hot environment by burrowing and remaining inactive and in the shade during the hottest part of the day. Sheep on pasture can go for weeks without drinking and may live and grow without drinking water.

WE HAVE RELATIVELY little data on the actual needs of animals for water under range or pasture conditions and the effect of restricted water intake on growth.

Scientists in South Africa have correlated growth rates of cattle and sheep with periods of drought and with periods of plentiful rainfall. They observed that animals lose weight during periods of dry weather. The period of greatest relative growth in South Africa follows periods of heavy rainfall by about 3 months. The scientists concluded that the most damaging effect of drought is the effect it has on plant growth and feed intake and that reduced intake of water is not the major factor in the lower growth rates.

S. S. Hutchings, at the Desert Range Station of the Intermountain Forest and Range Experiment Station in Utah, learned in a series of investigations that sheep on range gained an average of 3.4 pounds each in a 40-day period when they were watered daily. When they were watered every other day, they gained 0.8 pound each. They lost 6.0 pounds each when they were watered every third day. Sheep maintained on heavily grazed range and trailed to snow, which was the only source of water, lost an average of 11 pounds each in 10 days.

Under more intensive systems of animal husbandry, I. W. Rupel, at the Wisconsin Agricultural Experiment Station, learned in experiments that dairy calves fed skim milk and hay and offered water twice daily gained 1.8 pounds a day. Other calves, similarly fed but not given access to water, gained only 1.36 pounds daily.

V. W. G. MacEwan and V. E. Graham, in Canada, discovered that milking cows that had water before them at all times produced 5.59 percent more butterfat than when water was supplied twice daily.

Similar experiments at the Agricultural Research Center at Beltsville by T. E. Woodward and J. B. McNulty indicated that watering once or twice daily, as compared to watering from drinking cups, had little effect on milk production of low-producing cows, although a drop of up to 6 percent occurred when water was given high-producing cows only once or twice a day.

Studies by F. W. Atkeson and T. R. Warren, of the South Dakota Agricultural Experiment Station, failed to demonstrate that frequency of watering had any marked effect on milk production, although cows lost weight when watered once a day and gained weight when watered at least twice a day. When water was restricted to about one-half the usual allowance, milk production dropped from 18.3 to 14.1 pounds a day.

An accompanying table, taken from data of W. O. Wilson and W. H. Edwards, at the California Agricultural Experiment Station, illustrates the effect of lack of water on White Leghorn pullets maintained in a laying house in which the temperature was 90° F. Water was withheld from groups of birds for 24, 48, or 72 hours during a 7-day experimental period. Besides a loss in body weight, egg production dropped and so did intake of feed.

Water Restriction and Body Weight and Egg Production of White Leghorn Pullets

Water withheld	Body weight change (grams per day)		Egg production (eggs/6 days/bird)	
	Experimental	Control	Experimental	Control
24 hrs. .	—48	+6	2.7	3.9
48 hrs. .	—97	—5	1.9	4.4
72 hrs. .	(1)	(1)	1.5	3.6

[1] Body weight losses were 10, 15, and 19 percent on days 1, 2, and 3 of this test. Recovery to that of control hens occurred during the last part of the test when water was supplied.

For maximum efficiency, the water content of the animal tissues must be maintained within normal limits. Water is lost continually in the urine and feces and by evaporation from the body surfaces. In order to maintain constancy of tissue water, therefore, the total water made available to the animal must equal the output of water.

Animals obtain water from three sources: Water that is consumed as free water, the water that is contained in the feed, and the water that is made available during metabolic processes (metabolic water) in the tissues. (For every pound of starch, fat, or protein, respectively, that is oxidized in the body, an estimated 0.56, 1.07, and 0.40 pounds of water, respectively, are produced.) The total water made available from the three sources when the animal is in water balance is the water requirement. The water requirement should not be confused with water consumption, which accounts only for the water taken as free water. Water intake usually refers to free water plus that contained in the feed.

The determination of water requirements involves detailed studies of the complete water balance of all classes of animals under a wide variety of feeding conditions and environments. Such studies have been made only for some classes of cattle under a restricted set of conditions. Even from those studies—because of individual variations among the animals and the variable effects of rations and level of production—we can draw no clear-cut conclusions that would help us list accurately the requirements of the farm animals.

Many factors influence the intake of water by livestock. In a general way it parallels the consumption of dry matter in the feed when animals are on dry feeds. Cattle and sheep drink 3 to 4 pounds of water to each pound of dry matter. Pigs, horses, and fowl consume about 2 to 3 pounds of water per pound of dry feed. Those ratios and, therefore, water consumption also tend to be higher on feeds of high protein content and on rations containing a high proportion of fiber.

Another outstanding characteristic of feeds that affects water consumption is the water content of the feed itself. Variations in water consumption due to this factor are most pronounced in cattle and sheep. Mr. Atkeson and Mr. Warren, in South Dakota, learned that dry cows fed only hay consumed 93 pounds of water a day; when they were fed hay and silage, they consumed only 74 pounds a day. Sheep on good pasture drink little or no water; on dry pasture they may consume up to 15 pounds daily. The water consumption of cattle will also be reduced on good pasture but not to the same extent as that of sheep.

The level of production will also affect water consumption a good deal. The total water intake of steers on maintenance rations averages about 36 pounds a day; on fattening rations it is about 72 pounds a day. Dry Holstein cows take in about 90 pounds of water a day; when producing 20 to 50 pounds of milk a day they may consume 160 pounds of water a day. Cows producing 80 pounds of milk a day drink as much as 190 pounds a day. Lactating ewes need 30 percent to 50 percent more water than other ewes. A sow may consume 38 pounds of water a day the week before farrowing and 45 pounds a day the week after farrowing. Nonpregnant sows consume

Effect of External Temperature on Water Consumption

Hogs	*Water consumption Pounds per hog per hour*		
Temperature (°F.)	*75–125-lb. hogs*	*275–380-lb. hogs*	*Pregnant sows*
50	0.2	0.5	0.95
60	.25	.5	.85
70	.30	.65	.80
80	.30	.85	.95
90	.35	.65	.90
100	.60	.85	.80

Dairy cows	*Gallons per day per cow*		
Temperature	*Lactating Jerseys*	*Lactating Holsteins*	*Dry Holsteins*
50	11.4	18.7	10.4
50–70	12.8	21.7	11.5
75–85	14.7	21.2	12.3
90–100	20.1	19.9	10.7

Laying hens	*Milliliter per bird per day*	
Temperature	*White Leghorn*	*Rhode Island Red*
70	286	294
80	272	321
90	350	408
100	392	371
70	222	216
70	246	286

Water Consumption of Sheep

(Pounds of water per day)

Conditions	
On range or dry pasture	5–13
On range (salty feeds)	17
On rations of hay and grain or hay, roots and grain.	0.3–6
On good pasture	Very little if any.

In these experiments water was available for consumption.

Water Consumption of Pigs

(Pounds of water per day)

Conditions	
Body weight=30 lbs	5–10
Body weight=60–80 lbs	7
Body weight=75–125 lbs	16
Body weight=200–380 lbs	12–30
Pregnant sows	30–38
Lactating sows	40–50

Water Consumption of Chickens

(Gallons per 100 birds per day)

Conditions	
1–3 weeks of age	0.4–2.0
3–6 weeks of age	1.4–3.0
6–10 weeks of age	3.0–4.0
9–13 weeks of age	4.0–5.0
Pullets	3.0–4.0
Nonlaying hens	5.0
Laying hens (moderate temperatures)	5.0–7.5
Laying hens (temperature 90° F.)	9.0

Water Consumption of Growing Turkeys

(Gallons per 100 birds per week)

Conditions	
1–3 weeks of age	8–18
4–7 weeks of age	26–59
9–13 weeks of age	62–100
15–19 weeks of age	117–118
21–26 weeks of age	95–105

Water Consumption of Cattle

Class of cattle	*Conditions*	*Water consumption (Pounds per day)*
Holstein calves (liquid milk or dried milk and water supplied).	4 weeks of age	10–12
	8 weeks of age	13
	12 weeks of age	18–20
	16 weeks of age	25–28
	20 weeks of age	32–36
	26 weeks of age	33–48
Dairy heifers	Pregnant	60–70
Steers	Maintenance ration	35
	Fattening ration	70
Range cattle		35–70
Jersey cows	Milk production 5–30 lbs./day	60–102
Holstein cows	Milk production 20–50 lbs./day	65–182
	Milk production 80 lbs./day	190
	Dry	90

325862°—55——3

about 20 pounds of water a day; when 77–114 days pregnant they consume about 30 pounds a day. The water consumption of mature pullets is about 3 to 4 gallons for each 100 birds; 100 laying hens need 5 to 7 gallons a day.

The other major factor that may affect the intake of water is environmental temperature. Considerable work has been done at the California and Missouri Agricultural Experiment Stations on the effects of temperature on consumption of water and the related physiological alterations in dairy cattle, swine, and chickens. The experiments showed that as external temperature increases from about 50° to 100° F., the amount of moisture lost by evaporation from the body surfaces also steadily increases. Moisture loss by evaporation has the effect of enabling the animal to withstand better the effects of increased temperatures, because it can get rid of large amounts of heat efficiently. This mechanism whereby heat is lost reaches a high development in horses, which sweat profusely. It has a limited effect in most domestic animals, which sweat less. Increased evaporative loss, on the other hand, raises the need for water in order to keep the water balance of the tissues.

In all the experiments, consumption of water increased as the temperature went up. At the highest temperatures, however, no further increase in consumption occurred; in some instances it declined. At those temperatures, feed consumption, milk production, and egg production fell and body temperature increased. The observations indicate that increased water consumption as a means of combating high environmental temperatures has its limitations.

So we see that the water needs of livestock fluctuate widely—particularly the needs of ruminants, whose rations may vary a great deal in composition and water content.

Data on water consumption of livestock and poultry are given in tables on page 17. The values given for poultry and hogs will be applicable generally and will actually approximate the water requirements, because the feeds usually given them contain little water and do not vary widely in composition. The figures given for cattle and sheep cover the maximum requirements, but because data on consumption on pasture or range are lacking and because the water content of rations varies widely, the minimum amounts cannot be stated accurately.

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The Needs and Uses of Water by Plants

Leon Bernstein

Most actively growing plants or plant parts contain more water than solids.

The water is not inert material or "filler"—the water in plants, as in all living matter, contributes as much to the essential properties of life as do the more complex proteins, the fatty compounds, carbohydrates, and minerals.

Many people believe that life originated in the sea. The relationship of primordial life to water therefore was direct and relatively simple. When the terrestrial forms developed, water supply became a critical factor, and plants underwent profound changes in structure during the long process of adapting themselves to living on land.

The cell is the unit of living matter. The structure of plants can be understood only in terms of the cells that constitute them. Plant cells are diverse in size, form, and composition, but their basic structure is much the same.

The average plant cell measures only about one one-thousandth of an inch in diameter.

A LEAF CELL, such as is found in the interior of the leaves of most plant species, consists of a relatively rigid outer wall and its contents. The cell wall surrounds and is in close contact with the protoplasm, the viscous fluid that is the living matter of the cell. Cell walls—familiar to us in the form of natural fibers such as cotton and hemp, and in aggregate form as wood—consist largely of complex carbohydrates built up by the combination of numerous sugar units. The cell wall, because of its rigidity, determines the shape of cells. Large numbers of cells adhering at points of contact determine the shape and form of the plant.

Chemically, the protoplasm inside the cell wall is complex. Next to water, proteins are present in greatest abundance; more than any other class of constituents, they are responsible for the unique properties of living matter. The properties of proteins that make them the principal building material of living matter and the substances that control most of the life processes are actually properties of protein solutions in water. The distinction may be illustrated by comparing the obvious properties of a protein, such as egg white, in the fresh and dehydrated forms.

Water, proteins, and the other constituents of protoplasm, including the fatty materials, sugars, salts, and many other derivatives, thus compose a complex system, no part of which can be omitted without fundamentally altering the potentialities of protoplasm.

The protoplasm contains a number of distinct structures, which regulate or perform specific cellular functions. The nucleus carries the heritable factors, or genes, which transmit certain characteristics from generation to generation and control the development of the individual cells in conformity with the inherited potentialities. In green tissues, chloroplasts (in which the green pigment, chlorophyll, is localized) act as the centers in which light energy is absorbed to convert carbon dioxide and water to sugars.

The protoplast, or the unit of protoplasm in a cell, also contains one or more vacuoles, which are droplets of a watery solution of various salts, sugars, and other materials, completely surrounded by protoplasm. In the water relationships of cells, each part, the cell wall, the protoplasm, and the vacuole, has a necessary and distinct function. The cell wall permits the free passage of water and most dissolved materials, but the protoplasm limits the passage of the latter.

Before we can consider the manner in which the distinctive properties of the cell wall and protoplasm regulate the water relationships of the cell, we must understand some of the properties of solutions.

THE COMPONENT PARTICLES of solid matter occupy relatively fixed positions, but the particles of gases, liquids, and solids in solution move about freely and at random. All parts of a solution therefore tend to achieve equal concentration. An example: A lump of sugar dropped into a tumbler of water dissolves, and the sugar particles begin to disperse throughout the water as they become detached from the lump.

As a final result of this process of diffusion, the number of sugar particles in any given volume of water anywhere in the tumbler eventually becomes equalized. Diffusion affects the water in the tumbler as well as the sugar; the water particles likewise tend to become evenly distributed throughout the tumbler, as a result of their random motion.

Let us consider a single plant cell immersed in a droplet of rainwater.

The water bathing the cell contains

little dissolved material. The water inside the cell contains sugars, salts, and various other compounds in solution. The dissolved materials tend to move out of the cell, and water tends to move into the cell by the process of diffusion, each material tending to equalize its concentration in the water-droplet-cell system. The protoplasm restricts the movement of most dissolved materials much more than that of water, however, so that, in effect, the water moves into the cell while the dissolved materials in the cell are largely retained within it. The water accumulates in the vacuole of the cell and builds up a pressure, which forces the protoplasm against the cell wall and keeps it fully distended. A cell in this condition is said to be turgid. The diffusion pressure of water in the cell, which is a measure of the tendency of water to move out of the cell, increases as the turgidity of the cell increases. At equilibrium, the turgor of the cell sufficiently increases the diffusion pressure of water in the cell to compensate for the lower concentration of water due to the presence of dissolved materials.

If the droplet of rainwater is replaced by a moderately strong sugar or salt solution (so that the water is in greater abundance in proportion to dissolved materials inside the cell than outside) water begins to move out of the cell. The pressure inside the cell is relieved, and if the outward movement of water continues, the cell loses its turgor and becomes flaccid. The movement of water across a membrane such as the protoplasm, which is more permeable to water than to the materials dissolved in it, is called osmosis.

The basis for the osmotic movement of water is the difference in permeability of the protoplasm to water and to substances in solution in the water. If the protoplasm is injured or killed, as by excessive heat or poisons, it loses its property of differential permeability, and dissolved substances diffuse out of the cell. A piece of red beet tissue loses very little of its water-

A Leaf Cell

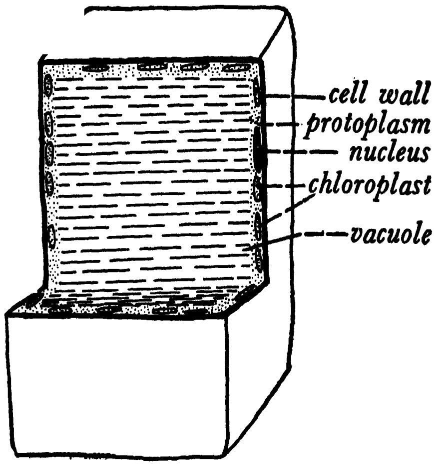


Diagram of a leaf cell, a part of which has been cut away to show the relationships of cell wall, protoplasm, and vacuole.

soluble red pigment if immersed in tapwater, but if the water is heated enough to injure or kill the beet cells, or if some poison is added to the water, the red pigment rapidly diffuses into the water. The tissue becomes flaccid as it loses the ability to retain dissolved materials.

PLANT CELLS tend to absorb water by another process, which is characteristic of many finely divided or dispersed materials. Water is strongly attracted by the large surfaces exposed by such materials and is held with considerable force. Proteins and carbohydrates, such as the cellulose of the cell wall, represent a high proportion of the solids in plant cells, and some of the water in the cell is held by the attractive force they exert. Dry wood, largely cellulose, will take up water and swell or warp. The process of water uptake by such materials is called imbibition and is largely responsible for the initial water uptake by dry seeds.

We can now appreciate more fully the advantageous position of aquatic plantlife with respect to its water supply. The protoplasts need only main-

tain the ability to retain the dissolved substances which the cell manufactures or absorbs, and (if the bathing medium is not too concentrated) the plant cells will obtain water by simple diffusion, or osmosis.

WITH THE DEVELOPMENT of land forms, the parts of the plant that are exposed to the air became subject to desiccation by the evaporation of water from the cells. The evaporative loss of water from plants is called transpiration. By far the greatest portion of the water taken up by the roots of a plant is lost by transpiration.

For every pound of dry matter in a plant, we commonly find about 5 or 10 pounds of water, but for each pound of dry matter produced, the plant must absorb several hundred pounds of water; the difference between the 5 or 10 pounds and the several hundred pounds represents water lost by transpiration. By contrast, the aquatic plant has to absorb only the water required for its growth; that is, the 10 pounds or so per pound of dry matter constituting the plant body. It is evident, therefore, that land plants must have efficient means for absorbing water, for distributing it throughout the plant, and for controlling water loss as much as possible.

THE CHARACTERISTICS of land plants which have made possible their survival and extensive development in an environment so demanding with respect to water supply are represented in the drawing on the next page. Because most of the water used by land plants must be absorbed from the soil in which they grow, root systems must be extensively developed. The underground parts of most land plants permeate a volume of soil as large as—or even larger than—the space occupied by the aboveground parts, and the finely divided root system presents an enormous surface area for water absorption. That large absorbing surface is augmented by the development of numerous fine root hairs on the young, growing roots. The total length of the roots developed by a single grain plant, such as wheat, may be tens of miles, and many millions of root hairs may increase the already large absorbing surface by as much as ten times or more.

The conduction of water is facilitated by the development of specialized, greatly elongated cells in the roots, stems, and leaves of land plants. After the cells have grown, the protoplasts degenerate and disappear, leaving a long, hollow tube, or tracheid, which presents a minimum of resistance to the movement of water. The end walls of the cells in many species are digested away as the cells mature, and resistance to the flow of water is reduced further. Such units are called vessels. Vessels and tracheids and the cells that remain alive form the xylem tissue or wood, most extensively developed in woody plants.

The xylem affords a continuous system of hollow tubes from near the tip of the root, through the root and stem, and into the leaf, where it is part of the familiar leaf-vein network. The woody tissue of stems and roots also performs other functions in a land plant, notably anchorage and mechanical support. Adaptation to a terrestrial habitat resulted in modifications of the plant body with respect to many features, and the discussion of water relationships is not intended to minimize the importance of the other features.

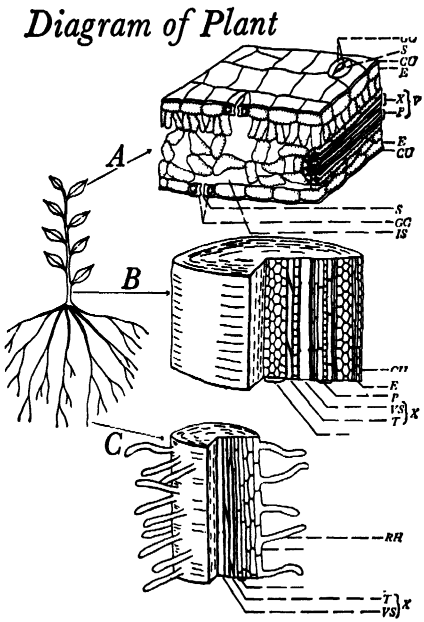
The leaves of plants typically are flattened structures, which present a maximum surface for the absorption of light energy and the interchange of gases with the environment. These are necessary features for photosynthesis, the process whereby green plant tissue manufactures sugars from the carbon dioxide absorbed from the air and water obtained from the soil. Oxygen also is produced in the process.

A leaf is constructed of a number of specialized cell types. The interior of the leaf is made up largely of the green, or chloroplast-containing cells loosely arranged, with continuous but irregu-

lar airspaces between the cells. The airspaces are interconnected and lead to the exterior atmosphere through numerous minute pores—stomates—in the surface of the leaf. Thus, as the green cells take up carbon dioxide, more of this gas enters the leaf by diffusion from the surrounding air, while the oxygen produced by the cell moves out of the leaf by the same process. The cell walls inside the leaf are saturated with water, which evaporates from their surfaces and also diffuses into the surrounding air. Most of the water lost by the plant passes through the stomates as water vapor by transpiration.

The plant has to conserve water, but it cannot completely exclude the surrounding air, with which it must maintain necessary exchanges of gases. Transpiration, however, is restricted by the presence of a waxy covering, or cuticle, on the outer surfaces of leaves and young stems. Comparatively little water is lost through the cuticle. With older, woody stems, whose growth in diameter results in the rupture of the cuticle, water loss is controlled by the development of a layer of cork cells, whose thick, impervious walls restrict loss of water. Small areas of spongy, loosely arranged cells, the lenticels, permit gaseous exchange through the cork layer, or outer bark.

Associated with the stomates are pairs of specialized cells, the guard cells. The pore, or stomate, is the space between a pair of guard cells. If the guard cells are fully turgid, the stomate is open to its fullest extent. As the guard cells lose turgor, they approach each other, closing the stomate. These movements in the guard cells, which control the stomatal opening, are brought about by differential thickness of the cell walls. The walls next to the stomate commonly are thicker than those on the opposite side of the guard cells. An increase in turgor forces out the thinner walls and pulls the two guard cells apart, opening the stomate. If the leaf loses water faster than it can be replaced, the leaf



A diagram which shows the relationships of the parts of a plant that are concerned with absorption, conduction, conservation, and loss of water. A, is an enlarged portion of leaf cut away to show internal structure; B, enlarged segment of stem; C, enlarged segment of young root. Sectors have been removed to expose cells in the interior. GC is a guard cell; S, stomate; CU, cuticle; E, epidermal cell; X, xylem; P, phloem; V, vein; IS, intercellular space; VS, vessel; T, tracheid; PI, pith; RH, root hair.

cells become less turgid, and as the guard cells lose turgor, they begin to close, eventually reducing water loss by the closure of the stomates.

The movement of guard cells is also conditioned by light. Photosynthesis is initiated in the presence of light. That lowers the acidity of the guard cells and favors the conversion of starch into sugar. The increase in sugar, resulting from these processes, increases water absorption from adjacent cells, so that turgor increases and the stomates open. Those processes are reversed in the dark; respiration produces carbon dioxide and sugars are converted into insoluble starch in the chloroplasts. The changes lower the sugar content of the guard cells, they lose water to adjacent cells, and the stomates close.

Because most of the water absorbed by land plants is lost by transpiration, the rate of water uptake must depend largely on the rate of transpiration. The mechanics underlying this relationship are fairly simple. Some of the cells of the leaf are directly in contact with the water-conducting elements of the leaf veins. Others have indirect contact through other cells. When water is lost by transpiration, the turgor of the leaf cells decreases, and they tend to absorb water from the water-conducting tissues with increasing force. Thus the loss of water from the leaf means that more water is pulled into the leaf. That, in turn, causes more water to move along the water-conducting elements from the root cells, thereby increasing the intensity of water absorption by the root cells in contact with the soil moisture. The whole process is therefore a chain reaction, in which the controlling element is the rate of water loss by transpiration.

According to this theory, the water in the xylem elements should be under tension, because of the pull exerted by the leaf cells. That has been demonstrated by cutting into the xylem cells of the stem while the part to be cut is immersed in a dye solution. The flash-like movement of the dye into the cut xylem elements supports the view that the water in these elements is actually under tension when transpiration is rapid. On the other hand, when transpiration is very slow, and soil moisture is adequate, appreciable positive pressures may build up in the xylem elements. Under such conditions, cutting into the xylem results in "bleeding." The volume of water made available to the plants by this process is, however, small when compared with the volumes lost during rapid transpiration.

SINCE TRANSPIRATION is the key process in the utilization of water by plants, the factors governing it are important. Transpiration involves the evaporation of water in the airspaces in the leaf and its diffusion out into the surrounding atmosphere. Within the leaf, the airspaces are nearly saturated with water vapor. Diffusion into the surrounding air, which is primarily through the stomates, is proportional to the difference in concentration of water vapor between the leaf spaces and the air around the leaf. Other factors being equal, therefore, the lower the water vapor content, or relative humidity, of the air, the more rapidly will water be transpired.

As leaves absorb solar radiation, they tend to become warmer than the air, the temperature difference being frequently as much as 5° to 10° F. The amount of water that can be held by saturated air increases as the temperature increases. Warming of the leaf by the sun's rays, therefore, increases the concentration of water vapor in the leaf and favors more rapid water loss.

It is not surprising, therefore, that the rate of transpiration follows a daily cycle that tends to parallel light intensity. By far the greater portion of water is lost during the daylight hours, and the rate of loss is most rapid during the middle of the day.

Transpiration tends to increase the concentration of water vapor in the air around the leaves. That would tend to decrease further loss of water from the plant. Air currents, by blowing away the accumulated water vapor, counteract the tendency.

CONTINUED TRANSPIRATION is possible only if the plant has a continuing supply of available moisture. If the supply becomes depleted or if loss of water exceeds the rate of water uptake, the plant eventually wilts, the stomates close, and transpiration is curtailed. While such control by the plant may prevent or delay serious injury or death, it is not without cost to the plant. Turgor, the distended condition of the plant cells, is necessary for continued plant growth, and a decrease in turgor, or wilting, is reflected in retardation or inhibition of growth.

A severely wilted plant, which has

closed stomates, cannot carry on photosynthesis effectively because the necessary exchange of gases with the surrounding air is impaired. Water is also one of the raw materials in photosynthesis, being the substance which is acted upon in the light to produce hydrogen, the basic reaction in photosynthesis. The amounts of water used in photosynthesis are small compared to those lost, however, and even in a severely wilted plant, the decrease in photosynthesis results from a limited supply of carbon dioxide or injury to the protoplasm as a result of desiccation, rather than deficiency of water as a raw material for photosynthesis.

Although excessive transpiration may injure plants and reduce yields, very little can be done to control it under field conditions because factors such as temperature, light, and wind are difficult to modify.

We can, however, attempt to maintain an adequate water supply for the plant by providing soil conditions that permit the maximum development and activity of the roots. A healthy, active root system and an adequate water supply are the only practical answers to the problem of transpiration.

Although transpiration appears to be an unavoidable evil in the functioning of plants, some effects of transpiration tend to be beneficial. Plants function best in a relatively narrow range of temperature. Excessively high temperatures may be injurious or deadly. Since transpiration cools the plant tissues, especially the leaves, it contributes to the control of temperature. Other physical processes, such as conduction and reradiation of heat, however, are usually more effective than transpiration in cooling leaves.

In higher forms of plantlife, certain functions are restricted largely to specific organs, which are modified to perform the functions most efficiently. The roots absorb water and minerals for the whole plant. The leaves manufacture foods. The stem supports the whole unit in the most favorable position for its component parts. Of primary importance is the movement of materials, originating in or absorbed by a specific organ, to the other plant parts where they are needed.

Water is essential for all transport in plants, as the transported materials move along as solutions. Sugars and other complex compounds move down from the leaves, where they are synthesized, to the stem and roots in the bark tissue, known as phloem. Minerals largely move in the xylem or wood elements, where they are carried upward from the roots to the stem and leaves. Transpiration, by accelerating the movement of the stream of water in the xylem, tends to hasten the transport of materials—but that is of dubious value because the supply of minerals in the leaves is adequate even when the transpiration rate is low.

Even the highly specialized structures characteristic of plants in humid regions would not be enough to insure growth in the arid or subarid regions. There the native vegetation has undergone further modification to enable its survival. Some species, rather similar to those in the humid areas, are annuals, which complete their life cycle in a brief period and can use to advantage the limited rainfall in certain areas. The profuse blooming of plants in some deserts after spring rains often is due to them. After that burst of life, the plants die, and only the seeds remain to carry on the species in another year.

In plants that survive the year around, profound modifications of the plant body safeguard it against desiccation in the dry months. Leaves are characteristically reduced to scaly or spiny appendages or may be entirely absent. The stem takes over the functions of leaves. This reduction in exposed surface reduces transpiration.

Further reduction in surface may result from an increase in diameter of stems, as in the cylindrical or globular bodies of cacti, whose fleshy stems store large amounts of water. Their

cells are rich in mucilages, gums, and other materials that have a high affinity for water.

Other plant forms, such as shrubs and grasses, survive without those obvious modifications in their structure. They may have extensive and well developed root systems and relatively limited top growth. This affords a greater water-absorbing system in relation to the transpiring surface. The shrubs usually have small leaves. In some species a profuse growth of hairs shields the stomates and sometimes reduces evaporation by retarding the loss of vapor from the surface of the plant.

Rows of specialized cells in the upper epidermis of many grasses are sensitive to reduced supply of water. As the cells lose turgor, they cause the entire leaf to roll up and so shield the stomates and reduce a further transpiration. Thicker cuticles may be produced, and frequently stomates are depressed, the guard cells being recessed below the general surface of the leaf.

THE EFFECTIVENESS of the modifications depends on the fact that—in the whole chain of processes governing the movement of water into, through, and out of the plant—the greatest pressures controlling the flow are those that govern the movement of water from the airspaces in the plant into the surrounding air. The pressures governing diffusion of water vapor out of the leaves even in moderately moist air tend to be about 100 times greater than those governing water movement into and through the plant. Effective control of transpiration is most readily obtained by a partial blocking of the pathway along which diffusion into the external atmosphere occurs.

Thus it is apparent that plants have evolved diverse adjustments in response to dry environments. Regardless of the nature of the modifications of structure and function, these plants are generally characterized by limited growth, especially of the aboveground parts. Growth and yields can usually be increased markedly if water is supplied in greater abundance.

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Water and the Micro-organisms

Paul R. Miller and Francis E. Clark

Without water there would be no micro-organisms, those myriad, minute, living forms whose bodies consist largely of water in which other vital materials are combined or dissolved.

Nearly every substance is a substrate, or foundation, on which some one of these microscopic forms may feed and grow. Some of the organisms are beneficial. Others cause a great deal of trouble. Some grow in water, and some in soil. Some live on dead or decaying vegetable or animal matter.

Some—the pathogenic micro-organisms—may invade the tissues of living plants or animals or human beings, in which they cause disease.

We first take up the water require-

ments of one group of micro-organisms, the fungi, and most of our discussion is devoted to the plant-pathogenic fungi.

The fungi are extremely important to mankind. They may be helpful or harmful. The antibiotics that have helped in the treatment of diseases are mostly growth products of fungi. Penicillin, for instance, is produced by some kinds of the common blue mold fungus, *Penicillium*. But fungi are responsible for many destructive plant diseases. The more we know about the factors that affect the growth of the fungi, including their water relations, the better we can utilize the beneficial forms and the more effectively we can control the destructive kinds.

At one or more of the decisive periods in the life processes of land-inhabiting as well as water-inhabiting fungi, water in some form is vital to further development. The amount of water needed at any one time and the manner of action varies according to the particular fungus. Often, also, for the same fungus the amount required is not fixed but depends somewhat on other factors, especially temperature.

These critical stages may include the liberation of the spores, which are the reproductive structures, from the stalks on which they are produced or the containers in which they are formed, actual dispersal of the spores to nearby or distant places; the coming to rest of the spores on the suitable substrate or host plant; germination of the spores to renew the life cycle; and, finally, the growth of the fungus on its substrate or in its host. Given the proper moisture conditions at each one of the stages, pathogenic fungi can start destructive epidemics.

The necessary water may be obtained from free (that is, liquid) water like rain or dew, from fog, and from water in the soil. Also, the air at all times contains water in a gaseous state in amounts that are measured and expressed as relative humidity. Quiet air surrounding a plant even on a dry day may be much wetter than the general atmosphere because evaporation from the leaves raises the humidity within the limited space.

In the liberation of spores, water acts in many ways. Sometimes free water from rain or dew or irrigation is required. Rain in great drops or driven by wind breaks the spores from their stalks or from within an enclosing layer. The summer spores, or conidia, of the apple scab fungus (*Venturia inaequalis*) are loosened from their stalks (conidiophores) by wind-splashed rain. Clouds of spores are expelled from puffballs when large raindrops hit the papery outer layer with force enough to compress the fruit body. Spores of the chestnut blight fungus (*Endothia parasitica*) are liberated only during rain and only as long as the bark of the tree remains wet. Some of the downy mildew fungi require that the conidiophores emerging from an infected leaf be immersed in dew for most abundant formation of spores.

The water need not always be in a liquid form. Often a humid atmosphere is enough. In some of the downy mildew fungi, alternate expansion and contraction controlled by a hygroscopic mechanism releases the conidia from their branched conidiophores, which coil up or unwind, depending on the dryness or moistness of the air.

In other unique ways fungi utilize water in producing and freeing their spores.

An interesting example is a fungus that occurs commonly on a number of grasses. From its stroma (or compact, dense growth) on a cut stalk of grass, spores may be liberated for days if the cut end of the grass is kept in water so that the transpiration stream (water absorption) of the grass remains undisturbed and supplies the fungus with moisture.

Another fungus can discharge its spores in dry periods by drawing solely upon water stored within its own stromatal tissue. Other fungi depend on the water reserves of their hosts.

One remarkable fungus produces its aerial structures in damp as well as dry

atmospheres by a unique conservation method. Its spore case has a wall so made as to retard loss of water from evaporation; the fungus furthermore has an efficient system for conducting water through broad strands without cross walls.

But moisture is not always necessary for the liberation of spores. For the so-called dry spore fungi, an absence of moisture aids the freeing of spores.

When the spore mass—the sporangium—of the common black bread mold is exposed to dry air, the wall collapses and frees a mass of dry, powdery spores, which are blown away.

The fungus *Penicillium* belongs to another group, in which the spores float down in dry air. Blue mold contamination results if their final landing place should be uncovered food or culture plates in a laboratory.

IN SPORE DISPERSAL, water is not the only agent. Air currents, the insects, animals, and some other means all take part. Water, however, is a common and often the chief agent.

In the bird's nest fungi (*Crucibulum* and *Cyathus*) rain splashed into the spore-bearing cups often is dashed out again, carrying with the drops the egg-shaped bodies that contain the spores.

In some fungi the spores when dry are firmly attached to the substrate by a kind of mucilage in which they are embedded. Raindrops wet the surface and swell the mucilage, thus forcing the spores out of their enclosing case and floating them freely over the surface in a film of water. Later raindrops remove the freed spores elsewhere.

Rainwater percolating through the earth carries spores of many kinds of fungi down into the soil. The pathogenic fungi are thus put in a position to attack roots and underground stems. Rain trickling over the surface of tree trunks spreads certain spore stages, such as those of the chestnut blight fungus. The movement of the surface water, such as irrigation water, runoff water in erosion, or the drainage water from ponds, or brooks, or the headwaters of a stream, also can transfer spore masses.

Another type of dispersal utilizes hidden water, the water present in the contents of the cells. Discharge and dispersal of spores involves mostly the bursting of turgid, or swollen, cells. Water in some form is necessary to produce and maintain turgidity.

The numerous means by which this type of dispersal is effected suggest the activities of a fungus "micro-arsenal," strictly governed by the laws of physics and gravity, triggered by response to light, and adhering to the principles of flight. The mechanisms are efficient and often capable of sustained and repeated action. Ejection of spores from a turgid fruiting body is accomplished by the bursting of the cell wall, made taut by the hydrostatic pressure built up inside the cell. Drops of liquid under pressure are enclosed within a tightly stretched body, usually spherical in shape. The actual break may be explosive, and the spores are catapulted away from the fruiting body.

Other types of escape are equally efficient in freeing the spores. Often they are spectacular. Spores are dispersed in clouds or streams of spore masses or in tendrillike threads. They are ejected singly or in small groups. The fruiting bodies open by long, vaselike beaks, by minute, hinged lids, or by the bursting of the highly turgid cells along a line of weakness in the cell wall. In one group of fungi the fruiting bodies actually turn themselves inside out by the pushing out of an inner wall.

How do spores floating in the air or carried by winds come to rest, renew their cycles, and (in the case of pathogenic fungi) cause plant disease?

THE DESCENT OF THE SPORES present in the air onto suitable substrates is accomplished in several ways. A spore floating on the air currents or carried by the wind may become stuck to a stationary object in its path. Spores are deposited on varied surfaces in the course of being carried up or down or

sideways during the irregular mixing of small and large airmasses, called eddies; in settling by gravity from out of still air; during exchange of air at the layer between zones of turbulent air currents and zones of still air; and by rainwash.

Rain probably does the most to bring spores of small-spored fungi to the ground. Kept aloft in turbulent air, they are likely to float over and past solid objects unless picked up and given a ride to the ground by raindrops. Natural raindrops possess the greatest collection efficiency for most spores. For the vast number of leaf and stem parasites, however, raindrops are not effective in landing the spores on suitable substrates for their germination and growth. One or another of the methods we have mentioned is then operative.

GERMINATION begins and proceeds after the spores have landed in a favorable place under favorable conditions. Temperature and moisture usually must be held in balance, particularly in the small space around the plant on which the spore lands.

Many fungi need films of fluid water for germination. Others can germinate in water or a humid atmosphere.

Even though the air about us sometimes seems very dry, enough moisture for spore germination may exist at the plant level. That happens when the temperature of the leaf surface is lower than that of the surrounding air and moisture condenses out of the air onto the leaves. Sometimes, also, dew remains on the leaf surfaces for several hours during a day when air movement is too slight or the sunlight is not intense enough to cause evaporation. And, lastly, even when the humidity is not particularly favorable, germination can proceed in still air, probably because of stimulation by some gas exhaled or liquid excreted from the leaf surfaces.

The mechanisms for the germination of fungi are various. Some spores form germ tubes directly, usually in the presence of free water. The germ tubes are long, fingerlike structures that penetrate the host tissue.

Spores of other fungi put out a short, thick tube, the promycelium, on which are borne even smaller spores, which in turn produce the fungus threads, or hyphae, that grow into the host.

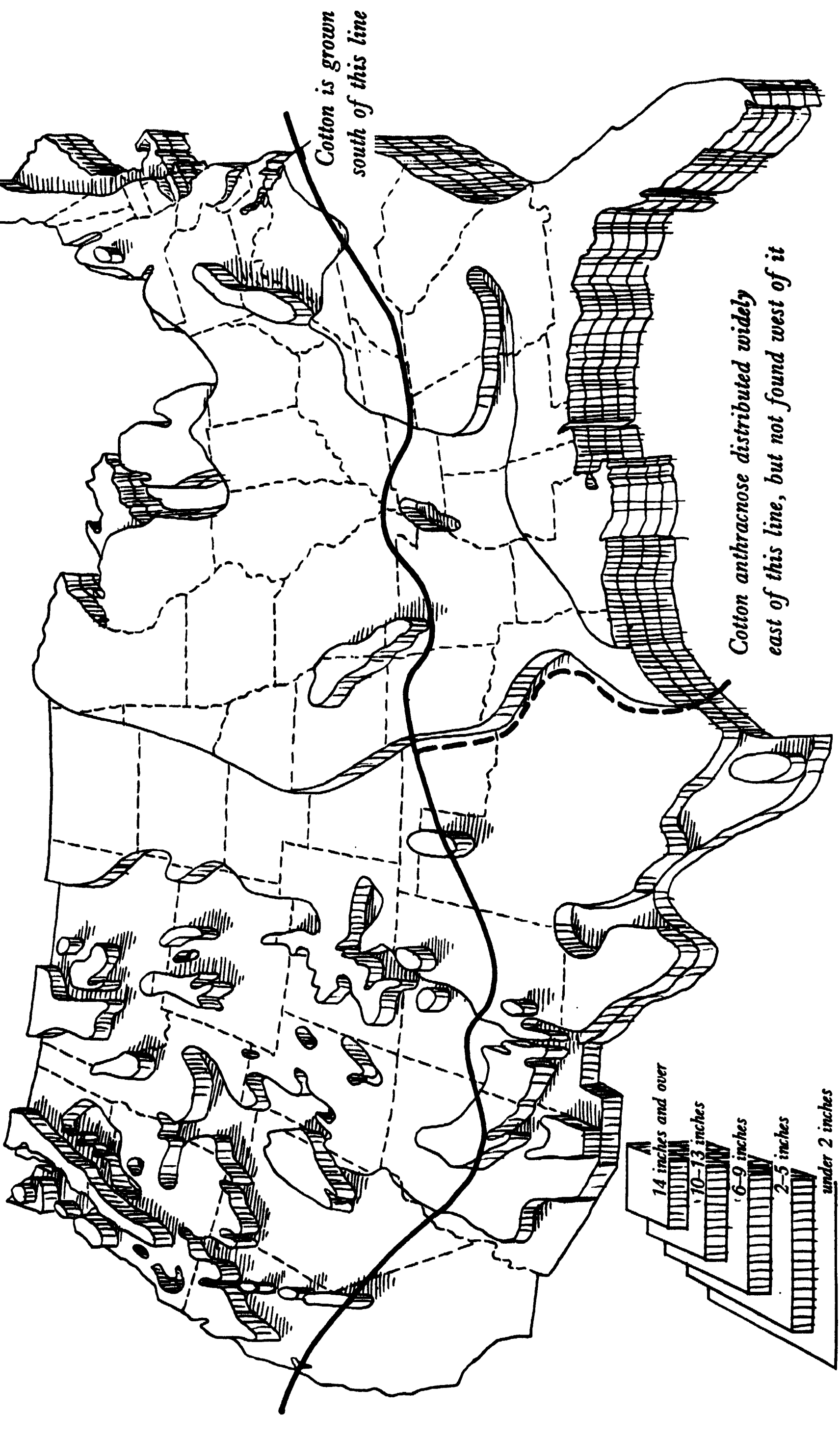
Other fungi reproduce by means of swimming spores, called zoospores, or swarmspores, propelled by one or more whiplike lashes. The swarmspores swim around for a while in the film of water on a leaf surface. Then they come to rest and produce germ tubes.

Germination by any method finally produces the fungus thread, or hypha, with which the fungus actually starts growing. The hyphae of some disease-causing fungi invade the host by taking advantage of openings, including the breathing pores, or stomata, on leaf surfaces of all plants, or the water pores that occur in groups on the margins of the leaves of some plants. Wounds that cause breaks in plant tissues also serve as paths of entry. Other fungi do not need already prepared entrances, but push themselves directly into the host tissue.

DISEASES ATTACK our crops when pathogenic fungi become established in the hosts. Water aids the onset, spread, and ultimate severity of plant diseases.

A striking example of the effect of rainfall in limiting the area of occurrence of a disease was discovered when cottonfields were examined to determine the incidence of cotton seedling diseases and boll rots. Cotton anthracnose (*Glomerella gossypii*) was found to be constant and important in the region of high summer rainfall in the eastern part of the Cotton Belt, although it is nearly nonexistent in the western part, which has less rainfall. Occurrence and absence of the disease are separated as though by a line through the eastern part of Texas and Oklahoma. The land on one side of the line gets an average of 10 inches of rain in summer; land on the other side has more than 10 inches.

Average Summer Precipitation in Inches



Within the eastern Cotton Belt, moreover, spore production is relatively abundant on cotton seed grown in the humid areas near the coast and generally lower in the inland sections, where humidity tends to be low. No spores are produced on cotton in the subhumid and semiarid regions of Texas and Oklahoma.

The map shows the relationship of average summer precipitation to the distribution of cotton anthracnose.

Knowledge of this distribution helps to control seedling diseases. Anthracnose, the most destructive cause of seedling disease in the eastern part of the Cotton Belt, is seedborne and can be controlled by seed treatment with fungicides. The soilborne infection most prevalent in the West, however, must be combated by chemicals and methods useful against soil fungi.

Rain spreads many plant diseases. The spores of the fungus *Colletotrichum lindemuthianum*, which causes anthracnose of dwarf and runner beans, are produced on bean pods in pink, slimy masses. Rain falling on the diseased plants makes drops that splash onto neighboring healthy plants and carry the infection to them.

In a humid atmosphere the spores of the potato late blight fungus, *Phytophthora infestans*, are produced on aerial conidiophores that emerge from the stomata of the leaves. Rain washes the conidial spores to the ground below and through the soil, where they infect the tubers.

We have many examples of the effect of high and low humidities on the occurrence and the spread of disease. Infection of lettuce leaves by the downy mildew fungus *Bremia lactucae* takes place when the air is saturated with moisture; that is, at 100 percent relative humidity. If the air is moving, conidia of the apple powdery mildew organism, *Podosphaera leucotricha*, germinate and infect apple leaves only at 100 percent relative humidity. On the other hand, several species of *Erysiphe*, another powdery mildew, can attack their hosts at low relative humidities—25 to 55 percent. Partial wilting of the host tissue in the dry air apparently aids the penetration by these fungi.

An example of a basic minimum humidity requirement for infection is given by *Helminthosporium oryzae*, which attacks rice. Infection by it cannot take place at less than 80 percent relative humidity.

Water is an efficient agent in spreading soil-inhabiting pathogenic fungi from place to place. Drainage, flood, and irrigation waters carry the organisms from infested soils to previously free areas. The tobacco black shank fungus, *Phytophthora parasitica* var. *nicotianae*, as well as numerous other species of *Phytophthora* and many other soil fungi, have invaded new locations in that way. They may become distributed throughout the basins of streams and rivers from original infestations in the upper valley, as is true of *Phymatotrichum omnivorum*, the destructive root rot fungus of the Southwest.

Moisture acts variously to favor or inhibit the production of disease by soil-inhabiting fungi. Some organisms require a great deal of moisture; others need rather dry soil. Among others, again, the requisite amount depends on the stage of development reached by the fungus.

Fungi in general are strongly aerobic; that is, they must obtain their oxygen from the air. For survival and growth of soil-inhabiting fungi, therefore, the soil must contain at least a minimum amount of air. Increase and diffusion of the air in the soil permits greater activity of soil organisms. The drier the soil, the greater the degree of soil aeration.

Thus the activity of most soil fungi depends on the balance between their specific moisture requirements and their need for air.

A root rot of avocado is caused by the soil fungus *Phytophthora cinnamomi*. Plantings on overirrigated or flooded locations where this fungus is present in the soil are severely affected. The excess of moisture prevents adequate

soil aeration. The rootlets of the host are injured because of lack of oxygen and other soil gases, and the fungus enters through the injured portions. Many other members of the genus *Phytophthora* need only high soil moisture to produce disease in various plants.

Another organism prevalent in cool, wet soils is *Plasmodiophora brassicae*, the cause of clubroot of cabbage. Soil moisture must be more than 45 percent of the water-holding capacity for infection by this fungus. The disease develops rapidly after a season of heavy rains, and severity increases along with soil moisture.

Sclerotinia sclerotiorum is a soilborne fungus that causes wilting and rotting of lettuce, cabbage, tomato, beans, peas, and many other plants. Its chief means of survival from season to season are sclerotia—compact masses of hyphae that produce the fruiting bodies of the fungus under proper conditions or may act as a sort of reproductive stage themselves. These sclerotia have been known to survive in dry soil for 11 years. If the soil is kept flooded with water, however, the sclerotia are destroyed in 6 to 12 weeks. Flooding is sometimes used to control them. High soil moisture favors the development of this fungus, but flooding results in a lack of soil aeration, which is probably the chief factor in the death of the sclerotia.

Among fungi favored by low soil moisture are some of the smuts that attack our cereals and grasses. Spores of oat smut (*Ustilago avenae*) germinate best at low soil moisture, and germination decreases as soil moisture increases.

NONPATHOGENIC micro-organisms do outnumber greatly the forms that cause disease. The range of moisture within which the thousands of species in this larger class remain alive is exceedingly wide. The range within which they grow is smaller and varies with the species. Airborne dust—even adobe brick sun dried many years ago—commonly contains viable organisms.

Bacteria survive the most extreme desiccation that laboratory technicians can devise, if the procedure is carried out at very low temperature. Micro-organisms in thoroughly dried materials are dormant and accomplish neither beneficial nor injurious activities. Their ability to survive dryness insures that they are almost always present to initiate decay when conditions again become favorable. Thus a sterilized food exposed to the atmosphere quickly becomes contaminated by dustborne microbes. A field soil remoistened after prolonged drought usually contains as varied a microflora as it did before drying.

Because micro-organisms commonly occur in dust, water that falls as rain, hail, or snow may contain a surprisingly large microbial population.

Many more bacteria are found in the raindrops at the beginning of a shower than after a long rain. Rain over cities contains more microbes than rain falling on upland forests or pastures. Rain falling on large cities may wash down yearly as many as 5 million organisms to each square yard. Such an estimate is based on the knowledge that rain contains from 1 to 25 micro-organisms per gram. (Expressed per teaspoonful, those numbers would be multiplied nearly 5 times.)

In water falling as snow, the numbers are usually larger than those in rain, presumably because of the larger surfaces of the snow particles. As many as 500 microbes per gram of snow and 20,000 per gram of hail have been encountered. Snow in the high mountains and the water from glaciers are practically sterile.

Surface waters also contain varying numbers of microbes. Streams below large cities and lake or ocean waters adjacent to cities usually contain many more organisms than does water more isolated from any human or domestic animal populations. Plant debris in water promotes micro-organic growth, just as a profuse microscopic life provides food in turn for larger aquatic animals.

The number of micro-organisms in the runoff from cultivated soil depends

on the amount of total suspended soil and on the amount of organic matter in the soil. Because much of the fresh organic material of soil is near the surface and many micro-organisms are associated with it and with the finer soil particles (which are readily subject to sheet erosion), conditions are ideal for loss of micro-organisms in the runoff.

J. K. Wilson and H. J. Schubert, in research at Cornell University, found there were 180 to 400 times as many organisms for each gram of solid material in the runoff as there were in the soil from which the runoff came. They concluded that the runoff from light rains carries relatively dense microbial populations because of the high proportion of finer and lighter material, while heavy rains produce a runoff carrying a sediment more nearly like that of the whole soil.

Because in most agricultural soils the organic matter content decreases with depth, a continuing erosion eventually yields a runoff whose microbial content is not nearly so large as that present in the uneroded normal topsoil of the same general area.

Many micro-organisms can flourish under a moisture tension that is much too stringent for the growth of higher plants. Plant roots cannot obtain water for growth from a soil atmosphere of appreciably less than 100 percent relative humidity. The lowest suitable limit usually is put slightly below 99 percent. Various microbial species can grow at relative humidities as low as 75 percent if temperature and other conditions are suitable.

Many agricultural products of low moisture content, if exposed long enough to an atmosphere of 75 percent relative humidity or higher, take up enough moisture to permit the growth of molds and bacteria.

Just as plants reach the wilting point at differing percentages of moisture content in different soils, the moisture content at which microbial growth can be started varies among different materials. For shelled corn this value is commonly taken as 15 percent moisture, dry weight basis. For alfalfa hay it is roughly 20 percent. Other factors, particularly temperature, are important. Soybeans can be stored safely at 14 percent moisture content for 2 to 5 months in cool weather, but a moisture content of 12 percent or lower is needed for safe storage during the summer.

At the favorable moisture content, it takes a longer time for spoilage to start as the temperature of storage is lowered from ordinary room temperature to near freezing. At a favorable temperature, more time is needed for microbial growth as the moisture content, either of the material itself or of the surrounding atmosphere, becomes less favorable.

T. J. R. Macara, in studies at Cambridge University, found that meat first dried and then stored at 100 percent relative humidity developed mold growth after 3 days, and after 7 days if it was stored at 85 percent humidity. In storage at 75 percent relative humidity, mold growth was delayed until 40 days. He found no microbial growth when the meat was stored 200 days at 65 percent humidity.

Foodstuffs and apparel usually can be stored successfully in subhumid and temperate climates if their moisture content at the start is below the critical content required for microbial growth. But the same materials, even though initially dried to an even lower moisture content, cannot be stored unprotected in a warm climate where high humidities may persist for rather long periods. Shoes, clothing, papers, and other common materials are quickly subject to a microbial attack under tropical conditions.

Once microbial growth begins in a material containing the barely sufficient, or threshold, moisture content, that substrate tends to become increasingly favorable because water is one of the commonest end products of decomposition. Assuming that micro-organisms are 30-percent efficient in converting foodstuffs to the substance

of their own bodies, the complete rotting of a bushel of shelled corn (if the conditions are favorable) can be expected to yield about 30 pints of water. Many of the organisms developed in the course of the decomposition themselves by that time would have decayed, and yielded additional water. The release of moisture is one of the reasons why rotting is autocatalytic—or, as it is sometimes said, one bad apple can spoil a barrel.

A moisture stress too rigid for microbial activity can be brought about by actual lack of water and by a high osmotic pressure. Brine has plenty of water, but its salt content makes it hard or impossible for micro-organisms to take water from the solution. Water, indeed, is actually withdrawn from the bodies of micro-organisms grown elsewhere and transferred into a concentrated salt solution. Different salts may inhibit microbiological development in different ways because of their specific ion effects, regardless of their osmotic pressure.

Many microbes can grow at higher osmotic pressures than plants can.

Many saline and alkaline soils are unsuited for cultivation not because of any lack of beneficial soil organisms or any restriction of microbiological activity that has to do with fertility. Indeed, the improvement obtained in an alkaline soil by an addition of sulfur hinges on microbial activity—certain bacteria render the sulfur effective by oxidizing it to sulfuric acid.

The best conditions for many desirable microbial transformations in the soil occur when there exists the maximum amount of water that is compatible with adequate aeration and the osmotic pressure of the water is suitable. For many microbial processes in soil, the optimum moisture content is the content present at the aeration porosity limit, or at 0.05 atmosphere of tension. As a rough approximation, this content is sometimes taken as 60 percent of the maximum water-holding capacity.

When soil water content goes down from the field moisture capacity to the permanent wilting percentage for plants, a negligible decrease occurs in microbial activity in the upper part of this moisture range. As the wilting point is approached, microbial activity drops sharply, and some organisms are checked entirely. Several factors can be responsible, but the decreasing solvent effect of the thinner moisture film and the inadequate diffusion of the waste or toxic products of microbial growth are the chief causes.

Different micro-organisms vary as to the moisture content at which they are most active. That is due largely to their differing ability to grow in the shortage of oxygen which develops as the soil pore spaces become filled with water instead of with air. Fungi as a group depend much more on adequate aeration than bacteria do, and fungal growth in soil therefore is the more sharply curtailed as conditions of moisture saturation are approached. When moisture content goes below field saturation, the fungi become increasingly numerous in the soil microbial population. In our laboratory we have enumerated 90 times as high a fungus population in a sandy soil maintained 15 days at 5.6 percent moisture as we encountered in the same soil maintained saturated.

Algae, in contrast to fungi, grow best in soil whose moisture content is not sharply below that at which gravitational water is present in the larger pore spaces. Algae commonly are present in ponded waters. The nitrogen-fixing algae are believed partly responsible for maintaining nitrogen fertility in rice paddies. At times algal growth becomes heavy enough in reservoir water to make it unfit in odor and in taste for drinking. Some pigmented algae, which can survive drought and then develop rapidly when conditions become favorable, sometimes impart a reddish or greenish appearance to soil surfaces after a few days of humid weather.

Growth of these algae is of little significance in soil fertility. Their

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growth energy is obtained from light, and their nutrient demand upon the soil is negligible.

The most favorable moisture content for many beneficial microbial changes in soil corresponds closely to the optimum for most of our common field crops. Minor variations may occur. The optimum soil moisture for nitrification is usually slightly lower than that for the decay of organic matter and for ammonification. That for nitrogen fixation is slightly higher. Increasing the moisture in the soil to saturation stops nitrification entirely. A less drastic increase in the water content more sharply curtails nitrification than it does ammonification and nitrogen fixation.

J. E. Greaves and E. G. Carter, of the Agricultural Experiment Station in Utah, discovered that both ammonification and nitrification usually are at their highest when the soil contains 60 percent of its water-holding capacity. Increasing the soil moisture to 80 percent of the water-holding capacity reduces nitrification to 10 percent, ammonification to 44 percent, and nitrogen fixation to 90 percent of the respective values determined at the optimum moisture content.

Flooding of soil, especially of a fertile soil containing any large amount of organic matter, encourages several undesirable bacterial transformations. Because numerous organisms can use oxygen that is in chemical combination with other elements, microbial activity under anaerobic conditions results in the reduction of various soil compounds. Some of these reductions adversely affect soil fertility and plant growth. Nitrogen present as nitrate nitrogen is subject to denitrification and loss to the atmosphere as gaseous nitrogen. Depletion of the soil nitrogen by micro-organisms then is in excess of their needs for nitrogen for building their own bodies. Reduction of nitrate nitrogen to atmospheric nitrogen involves the removal of all the combined oxygen. Partial reduction, or removal of only a part of the combined oxygen, results in the formation of nitrite, a compound that is toxic to plant roots when present in more than a few parts per million.

Both sulfates and elementary sulfur are reduced to sulfides in overwet soils. Hydrogen sulfide even in very small amounts is poisonous to plants; it is largely responsible for the foul odor that develops following the ponding of water on fertile soil or over plant debris. The anaerobic conditions resulting from waterlogging greatly increase the less highly oxidized forms of manganese at the expense of manganic oxides. Ferric iron similarly is reduced to ferrous iron. The greater solubilities of these reduced compounds render many waterlogged soils less suitable for plant growth. In the absence of organic matter to promote microbial activity, the solubility of iron, manganese, and certain other elements is not increased when soil is flooded.

The growth of micro-organisms in a flooded soil reduces percolation, or the movement of water downward through the soil. The reduced permeability appears to be due to a mechanical sealing, in which the soil pores become clogged with microbial bodies or their products of growth. In the construction of ponds for stock watering, such sealing is desirable, and straw or other food material may be mixed with the soil over which water is to be ponded in order to encourage a profuse development of micro-organisms. In the use of water ponding for recharging the underground water supply or for leaching excess salinity from the soil profile, microbes are undesirable to the extent that they interfere with the movement of water through soil.

Continuous waterlogging favors the preservation of organic matter; it does not favor decomposition of residues. The formation of peat exemplifies the effect of submergence on plants. Its formation requires an abundance of plant growth and insufficient drainage, and (with the exception of a few large basins like the Florida Ever-

glades) it occurs most commonly in temperate and subtemperate regions.

The failure of micro-organisms to mineralize submerged plant material thoroughly is due to several factors. One is that conditions of environment remain so much the same that different organisms fail to grow. Another is that aerobic fungi, which are primarily responsible for the decay of lignin (the woody constituent in plants) do not develop. Fats, waxes, and resins also largely escape decomposition. The sugars, starches, and plant proteins in bogs are first decomposed; the hemicelluloses and celluloses rot more slowly. Lignin and related materials therefore form a larger percentage of the organic matter remaining in peat than they do of the mosses, reeds, or sedges that are the source of the organic matter. Without air, sugars and starches are not completely oxidized to carbon dioxide and water but are only partially fermented and remain as organic acids. The acids, in the absence of an abundant supply of calcium to neutralize them, in turn inhibit decomposition.

Water is essential for the microbial activity, but only under an excess of water do micro-organisms fail to destroy plant material as rapidly as it can be formed. If drainage is adequate, organic matter does not accumulate in the humid Tropics, even though a tremendous tonnage may be produced yearly. But in the desert the annual rainfall, however small, is enough to permit microbial decomposition of all plant debris normally returning to the soil in that climate. Only in bogs does plant growth exceed plant decomposition. The two processes again come into normal balance only following recession of the water table or the building up of the accumulated organic matter to the surface of the water.

PAUL R. MILLER, *a pathologist in the Horticultural Crops Research Branch, Agricultural Research Service, began in 1935 to develop survey techniques and conduct field studies of diseases that occur on major economic crops, including peanuts, tobacco, cotton, and vegetables. Dr. Miller directs a plant disease forecasting service in cooperation with State agricultural experiment station pathologists, the United States Weather Bureau, and national farm chemicals and equipment associations.*

FRANCIS E. CLARK, *a bacteriologist in the Soil and Water Conservation Research Branch, Agricultural Research Service, is a graduate of the University of Colorado. Since joining the Department in 1936, he has had wide experience with the many micro-organisms concerned with nutrient transformations in soil. Much of his earlier service was at Kansas State College and Iowa State College.*

Trends in the Utilization of Water

Karl O. Kohler, Jr.

Five developments since 1940 have made us realize that we must take immediate steps to increase the conservation, improve the utilization, and expand the administration of our water resources. They are the Second World War, increases in population, shifts in industry, droughts, and pollution of streams and lakes.

Our population has grown far above normal expectations—and so has the amount of water needed to produce food and fiber and to fill the countless other needs people have for water. We estimated in 1940 that our population in 1975 would be 175 million. Since then we have had to revise that estimate to 200 million.

A major shift in population began at the outbreak of the war. The population of six Far Western States, for example, increased 25 to 52 percent between 1940 and 1950. The national increase was 15 percent.

Industrial expansion (and with it a heavy demand for water) moved west

and south. The availability of low-cost hydroelectric power drew a great deal of the wartime industry to the Pacific Northwest.

Large increases in the acreage under irrigation in the Far West and the rapid introduction of supplemental irrigation throughout the Midwest and in the Eastern and Southern States contributed to the much heavier consumption of water.

In 1939 there were 17,243,396 acres in irrigated farms in the 17 Western States. By 1949 the acreage had risen 39 percent to 24,270,566 acres. The increase in the remainder of the country was 105 percent—from 739,434 to 1,516,894 acres. The lands in irrigated farms in 1954 were estimated to be about 27.5 million acres.

Recurring droughts are a normal feature of climate in southern parts of the Great Plains. A critical period of drought began there in 1950. Similar conditions have existed in parts of the West, the Midwest, and the South. Municipalities had to find new sources of water to supplement or replace their supplies. Industries had to develop more of their own water supplies. Satisfying the needs of human beings and livestock for water became a serious problem in many sections.

The rapid industrial expansion since 1938, along with reduced streamflow in the drought areas, has accelerated the growing problem of pollution of streams and rivers. The seriousness of the situation is becoming more apparent to the public because pollution is discouraging industrial expansion in some regions. It also threatens numerous municipal water supplies.

The Geological Survey estimated that an average of approximately 4,300 billion gallons of water are released daily over the Nation through precipitation. What happens to it?

Upon falling on the land surfaces, part of the precipitation infiltrates into the ground. Part of it runs off over the ground surface. Some evaporates back into the atmosphere. The part that moves into the ground and the part that gets into the waterways becomes the Nation's primary water-development resource potentials. As portions of them are used, the waste water and return flow again move back into the waterways, where some percolation and evaporation take place. The residual flow continues until it is stopped at a lake, sea, or ocean, from where evaporation is a continuing process.

The process appears to be a simple explanation of the movement of the earth's water, but there are many vagaries about the relationships between and within the various factors that make up the water cycle. Necessarily, only average figures can be used in describing the factors that relate directly to the production of the country's water. The averages differ greatly between any series of years and with many local conditions.

The average annual precipitation in the United States is about 30 inches. About 22 inches, or 70 percent, of it may return to the atmosphere directly through the evaporation and transpiration. The remainder is available to streams and underground supplies.

The distribution of the precipitation on a national basis is not uniform. For example, the 17 Western States, which have about 94 percent of the irrigated land and 60 percent of our land area, receive only about 25 percent of the total precipitation.

The present fresh water demand on our surface and ground-water supplies is estimated by the Geological Survey to be about 63,000 billion gallons a year. That would approximate 4 percent of the total annual precipitation, or 13 percent of residual precipitation after accounting for the evaporation and transpiration losses. Of this supply, 83 percent is derived from surface waters and 17 percent from the ground water.

THE GREATEST SINGLE USE of fresh water in the United States is for irrigation—75 billion to 100 billion gallons a day, or about half of the fresh water we use annually.

The next largest water consumer is industry and steam powerplants, which are estimated to require daily about 70 billion gallons of fresh water used in the plants, besides the brackish and salt water used for cooling. Examples of industrial requirements are: 18 barrels of water to refine a barrel of oil; 300 gallons of water to make a barrel of beer; 10 gallons of water to refine a gallon of gasoline; 250 tons of water for a ton of sulfate wood pulp; and 600 to 1,000 tons of water for each ton of coal burned in a steam powerplant.

A large paper mill uses more water each day than does a city of 50,000 inhabitants.

We assign the highest preferential use for water to the domestic use. That water must be fit for human consumption and always be available. The Public Health Service reported an average water requirement of 137 gallons a person a day—about 60 gallons a day in communities of 500 or fewer people to about 180 gallons a day in cities of 10,000 population or more.

THE CHANGING AMERICAN diet now includes more animal products, fruits, vegetables, and sugar, and fewer grain products and potatoes. The increase in cropland requirements for food production because of the inclusion of more livestock products in our diet since the beginning of the Second World War is 0.14 acre a person, making a total of 2.5 acres of cropland needed to support each person. The equivalent of the production of 100 million acres may be required by 1975 to meet the requirements of our larger population. Because the land available for new production is limited, the increase in food requirements will be associated directly with use of water through irrigation and with the planned increase in production on lands now being farmed.

The application of water in irrigation is relatively inefficient, and the annual delivery to a farm may range from less than an acre-foot (325,850 gallons) up to more than 7 acre-feet (2,280,950 gallons) an acre. A cutting of alfalfa requires about 325,800 gallons of water an acre, and a crop of cotton, 800,000 gallons.

The efficiencies with which farmers apply their irrigation water to their crops may range from 15 percent to 90 percent—that is, from 15 to 90 percent of the water they turn onto a field will be made available to the plant roots; the remainder will be lost as runoff, deep percolation, and evaporation.

Problems related to the water table are many and varied and often are acute in the irrigated areas of the West. The use of surface waters for irrigation usually is accompanied by a rising water table, although in some conditions the percolating waters actually assist in the recharge of aquifers in adjoining areas or move downslope and interfere with the use of lower lying lands. When the water table rises too near the surface, it can produce drainage, salinity, and alkali problems, which must be corrected if cropping is not to be limited.

Of the many examples of the problems associated with the lowering of water tables, the following are cited by Harold E. Thomas in his book, *The Conservation of Ground Water*, published by McGraw-Hill Book Co., Inc., in 1951.

In the Santa Cruz Valley in Arizona, the withdrawal was 420,000 acre-feet in 1941, 730,000 acre-feet in 1945, and 1,250,000 acre-feet in 1949. The average annual replacement from all the sources was estimated in 1942 as 215,000 acre-feet. The water table dropped 50 feet in 9 years in the Eloy area.

The ground-water supply in the Antelope Valley in California appeared to be inexhaustible in 1910. Artesian wells had pressures of more than 10 pounds the square inch and flowed 900 gallons a minute. Many of the wells ceased to flow by 1920. The annual pumping rate in 1950 was 110,000 acre-feet; the estimated replenishment was 65,000 acre-feet. The water level

in the wells has been declining at the rate of 3 feet a year.

The town of Fessenden, N. Dak., drained most of a small aquifer with its municipal pumps in 20 years. It then found a new aquifer 5 miles away and in 4 years of pumping reduced its output from 100 to 10 gallons a minute. The town then had to haul 15,000 gallons a day from an adjoining city until another aquifer was developed 7 miles from town.

Pollution of the ground waters also occurs as a result of overdraft. Salt water has intruded into the underground water supply in parts of the Salinas Valley and along the coastal area near Los Angeles. In the El Paso area in Texas and in the Walton-Mohawk area in Arizona, overdrafts of wells have brought an increasing percentage of minerals in the waters. The water in some wells in the latter area is now adjudged "injurious to unsatisfactory" for irrigation.

Siltation is associated with the problems of water in several ways. Carl B. Brown, of the Department of Agriculture, in his book, *The Control of Reservoir Silting*, wrote: "Twenty-one percent of the Nation's (municipal) water supply reservoirs will have a useful life of less than 50 years, another 25 percent will last from 50 to 100 years, whereas only 54 percent will provide enough storage to suffice for present requirements (not estimated future needs) 100 years from now."

The loss of storage through siltation, besides making the water storage costly, can result in new problems when additional storage sites are not available. Reservoirs filled with silt have been abandoned and the water supply systems have had to be reorganized if no other storage sites were available.

Silty waters require treatment before they can be used for domestic consumption and for most industrial purposes. Suspended matter cuts down the penetration of the light on which plants depend for photosynthesis and the stimulation of growth and release of oxygen. The entire ecological balance—the natural beneficial interrelationship—is upset for the plant and animal life that live in or on the silty waters.

Problems in the arterial waterways and smaller streams have been aggravated by irregular water flows, varying from floods to insufficient low flows. With industry and municipalities expanding along the waterways, the damage from floods becomes greater.

The expansion and development of a modern system of waterways has become necessary to meet the demands of the country. The multiple problem of siltation, pollution, and uncontrolled waterflow must be solved to maintain these waterways at a reasonable cost to the Government.

IN SIGNING the Water Facilities Act on August 17, 1954, President Eisenhower said: ". . . we recognize that it is absolutely urgent to conserve and improve our water resources. . . . We cannot afford to waste water. . . ."

On May 26, 1954, the President appointed a Cabinet Committee on Water Resources and Policy to review all water policies and programs, to assist in the coordination of activities of the various Government agencies in the field of water, and to give consideration to national legislation on water resources. A task force in the Committee on Organization of the Executive Branch of the Government began to gather similar information in regard to national water legislation, and so did the Water Resources Policy Committee of the National Water Conservation Conference.

Extended planning for the utilization of the water resources of rivers must be carried out on the basis of river basins. Early legislation, such as the Reclamation Act of 1902, was intended primarily to aid irrigation in the West. The Flood Control Act of 1928 sought flood control in the Mississippi River Valley.

Today, river-basin planning by Federal and State agencies encompasses the interrelation of all the possible water uses in the watershed—naviga-

tion, flood control, irrigation, power, municipal and industrial water supplies, recreation, and wildlife. In 1928, the Hoover Dam was approved as the first multiple-purpose project specifically authorized by the Congress. Since that time the multiple-purpose consideration has been given to all similar structures built by the Bureau of Reclamation or the United States Corps of Engineers.

The multiple-purpose and interrelated use of river waters by private interests is also becoming more common as the water resources become more limited. The Big Creek Hydro System in California is an example. Since 1911, a private power company has constructed a series of four storage reservoirs and a regulating reservoir on Big Creek and the adjoining south fork of the San Joaquin. The system is operated in conformity with downstream water rights, and it is now possible to salvage flood flows in the spring and make them available to the downstream irrigators in the summer months of low streamflow. In normal supply years, the storage that can be made available is estimated at 80,000 acre-feet. Development of the four reservoirs has opened the area to new recreation interests, and resorts have been built near each of the lakes.

Farther downstream on the San Joaquin River, the Bureau of Reclamation also has constructed a reservoir to supply irrigation and domestic water and provide flood protection to the people in the San Joaquin Valley.

More than 100 bills pertaining to water pollution have been introduced in the Congress in the past 50 years. The Water Pollution Act was adopted in 1948.

It recognized the primary responsibilities and rights of States in the control of water pollution but made it possible for the Federal Government to assist the States through grants and loans for helping in pollution control work and for conducting investigations, research, surveys, and studies on pollution.

The Congress in 1954 made 1 million dollars available to the Public Health Service for the administration of the act and for research, studies, and surveys of the pollution problem; some of which was to be done on a cooperative basis with various States.

All States and Territories have some agency or division that works on problems of water pollution. In 1952, 24 States and Territories spent less than 28,000 dollars on pollution work; 15 States spent between 25,000 and 50,000 dollars; 3 spent between 50,000 and 75,000 dollars; 7 between 75,000 and 100,000 dollars; and 4 spent more than 100,000 dollars.

A study by the Department of Health, Education, and Welfare revealed that in 1951 there were 11,800 sources of municipal pollution and 10,400 factory-waste outlets into our streams and lakes; 6,700 of the municipalities had sewage treatment plants, but only 3,531 of the plants were of adequate capacity; 2,595 of the industrial plants were treating their waste water.

It was estimated that about 2.5 billion dollars would be needed to make new municipal plants and replacements and additions and enlargements to the present plants to bring them to satisfactory operations. The increased needs for the next 10 years would raise the cost to an estimated total of about 4.5 billion dollars by 1961.

Research organizations have been formed in various industries—such as the paper, canning, dairy, and oil industries—in an effort to find reasonable methods for treating their waste waters. The research is projected in view of the possibility of reclaiming some of the products in the waste water at the same time the purification process is taking place.

Examples of successful results of such research:

A chemical company, ordered by the State health department to abate its pollution, found the waste waters had a high vitamin content. Today the vitamins are the main product of the company.

A steel company in the Ohio Valley expended 516,000 dollars for a treatment plant to prevent dumping of flue dust into a river and ended up the first year of operation with a profit of 581,000 dollars through the recovery of reclaimed materials.

The distillery industry has for years extracted dried grains and protein concentrates for sale as cattle food.

Often, however, usable byproducts cannot be reclaimed from the waste waters, and the added cost of treatment will have to be absorbed as production expense.

According to B. A. Poole and Ralph H. Holtje, in the Journal of the American Water Works Association, July 1954, an example of industrial progress in pollution abatement is in Indiana where, between 1947 and 1953, 147 industries provided new treatment facilities at a cost in excess of 23 million dollars, an average of more than 3 million dollars a year. Even so, Indiana still had about 200 industrial plants without adequate treatment facilities.

A LARGE INCREASE in the proportionate use of the presently developed supplies of fresh water can well be made through conservation and reuse. The present supplies can be extended through:

Adoption of laws for controlling the conservation and distribution of surface and ground-water resources for beneficial use. Water conservation generally results from the establishment of new, or the improvement of old, water laws. Good water laws establish a control of use among competitive needs, protect the water rights of the users, maintain a control over the amount of available water, and reduce misuse and wastage.

Planning on a river-basin basis for natural resource developments where all interrelated water users are included.

Reclamation of what today is called waste water.

More efficient reuse of industrial waters.

Better land-use practices to conserve natural precipitation and reduce the movement of sediment.

More efficient handling and use of irrigation water to reduce the losses in transportation and increase the efficiency of application. The water saved can usually be used locally.

Intensified drainage, irrigation, and flood-control activities.

Reduction of evaporation from water surfaces. This opens a new field of investigation that may develop into a way to conserve water.

NEW SOURCES of water are being investigated and, to a degree, utilized. They include:

Reduction of losses through transpiration by native vegetation. It is estimated that in the 17 Western States alone nonbeneficial plants waste 20 million to 25 million acre-feet of water a year. If half of it could be salvaged it would provide annually water equivalent to 3 acre-feet on 1,700,000 acres.

More economical manufacture of fresh water from sea water. Research work to that end has been undertaken by the Department of the Interior.

"Cloud seeding" for the inducement or control of precipitation.

Additional development of underground and surface water.

As shortages appear, the less economical supplies will have to be developed at a greater cost per unit of water.

The water-supply problems in America will be serious for years to come, but they can be solved through the organized efforts of the Nation.

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Where We Get Our Water

From Ocean to Sky to Land to Ocean

William C. Ackermann, E. A. Colman, and Harold O. Ogrosky

The unending circulation of the earth's moisture and water is called the water cycle. It is a gigantic system operating in and on the land and oceans of the earth and in the atmosphere that surrounds the earth.

The cycle has no beginning or ending, but because our discussion must start someplace, we can think of it as beginning with the waters of the oceans, which cover about three-fourths of the earth's surface.

Water from the surface of the oceans is evaporated into the atmosphere.

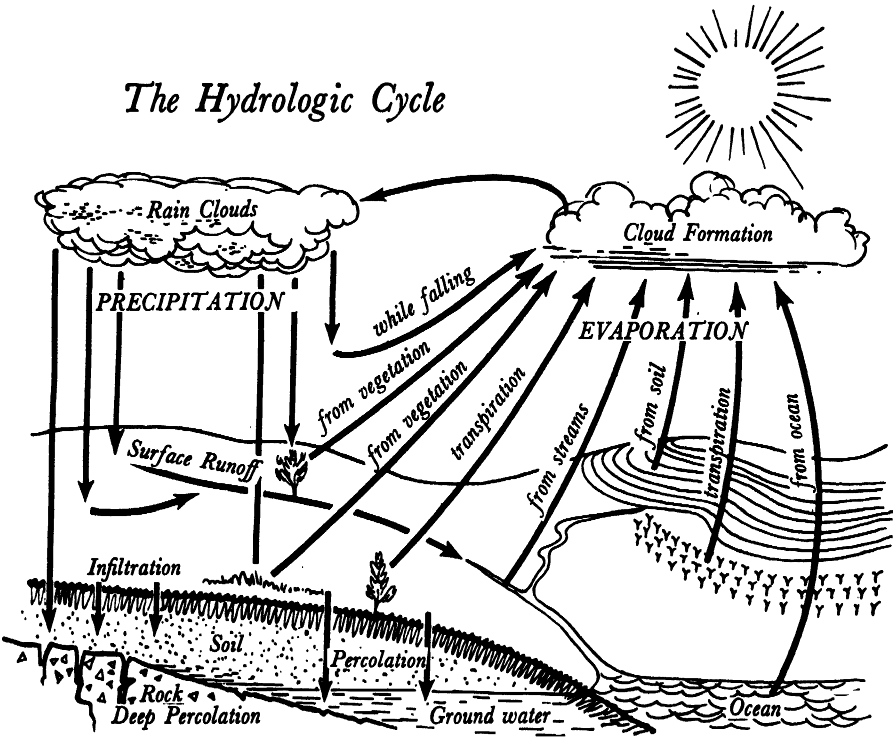
That moisture in turn is lifted and is eventually condensed and falls back to the earth's surface as precipitation.

The part of the precipitation that falls as rain, hail, dew, snow, or sleet on the land is of particular concern to man and agriculture.

Some of the precipitation, after wetting the foliage and ground, runs off over the surface to the streams. It is the water that sometimes causes erosion and is the main contributor to floods. Of the precipitation that soaks into the ground, some is available for growing plants and for evaporation. Some reaches the deeper zones and slowly percolates through springs and seeps to maintain the streams during dry periods. The streams in turn eventually lead back to the oceans, where the water originated. It is because of this never-ending circulation that the process has become known as the water cycle, or hydrologic cycle.

About 80,000 cubic miles of water are evaporated each year from the oceans. About 15,000 cubic miles are evaporated from the lakes and land surfaces of the continents. Total evaporation is equaled by total precipitation, of which about 24,000 cubic miles fall on the land surfaces—equivalent to a depth of 475 feet over all of Texas.

Circulation of the earth's atmosphere and moisture can be thought of as starting in the belt around the Equator. Because more of the sun's energy is received near the Equator than farther north or south, greater heating occurs there and the result is greater evaporation and a tendency for the air to rise. The warm, moist air flows outward from the Equator at high altitudes and because of the earth's rotation moves in a generally northeasterly direction in the Northern Hemisphere. By the time this air reaches about 30° North, which is about the latitude of New Orleans, it has lost enough heat so that it tends to sink. That downward-moving air generally divides at the earth's surface; a part of it moves southwesterly, as the trade winds do, back toward the



Equator, and a part moves northeasterly across the Temperate Zone.

Far to the north, near the North Pole, another circulation pattern is in operation. There a mass of cold air builds up and flows outward in a southwesterly direction. The polar air becomes warm in its southwesterly movement, and at about 60° latitude, which is well up in Canada, it becomes warmed sufficiently to rise and flow back toward the Pole. From time to time outbreaks of this cold polar air move out across the Temperate Zone. They are an important factor in causing our general rains.

If the earth's surface were entirely covered by water, the general circulation we just described would be regular and would occur in belts around the earth. The presence of large land masses changes this regular pattern, however, because the heating effect from the sun is different over land than over water. For example, in the winter the land masses cool more rapidly and are partly covered with snow, which reflects much of the sun's heat rather than absorbing it. The polar front therefore moves far to the south over the continents in winter. The result is the formation of cells of cold, high air pressure over the land masses, and cells of warm, low air pressure over the oceans. In the summer that situation is reversed.

The three broad storm types or conditions that operate within these general movements to bring us precipitation are the cyclonic; the convectional, or thunderstorm, type; and the orographic or mountain type.

The cyclonic type, or low-pressure-area type, is the familiar storm type that produces general rains over wide areas. The storms are particularly prevalent during winter.

Cyclonic storms are atmospheric waves, formed along the polar front by the interaction of the cold polar air masses and the warm tropical air masses. The waves move generally

from west to east in our latitude, following the general circulation pattern. An essential element of the cyclone is the warm-air sector on the south side of the revolving low-pressure system. The warm sector is made up of air originating in the tropical regions and contains the moisture, which undergoes change through lifting to become precipitation. This warm, moist air generally moves in a northeasterly direction and, being lighter than the existing cool air which it meets, rides up and over the wedge of cool, heavy air. The boundary plane between these air masses of differing temperature is referred to as the warm front. The result of lifting causes condensation and a broad belt of low-intensity precipitation.

To the northwest of the warm-air sector is a charge of fast-moving polar air, which moves through the warm air as a cold and heavy wedge. The leading face of this cold air is referred to as the cold front, and along it warm air is also lifted to cause precipitation.

Since the cold front moves more rapidly and is steeper, it usually results in intense precipitation, but for a short duration.

As a cyclonic storm passes a certain area in moving from west to east, precipitation usually starts with a slow, cool rain—or snow—as precipitation from the warm front falls through the underlying cool air. A period of warm and showery weather follows, as the warm sector moves across the area. The warm phase of the storm is ended by the rapid passage of the cold front, frequently with a hard shower and the beginning of a period of cold weather.

THE CONVECTIONAL TYPE of storm, or thunderstorm, is a second and familiar type. It ordinarily results in the most intense rainfall and occurs over rather small areas.

Thunderstorms occur throughout the country, but are most frequent in the southern part and in summer. Convectional storms are formed when, because of uneven heating, the air over a locality becomes warmer than the surrounding air. The areas of excessive heating may be over a city, whose streets and roofs are warmer than the surrounding countryside. The difference between hot, bare fields and cool woods or the difference between land and lakes produces this effect. Whatever the cause, where air receives additional heating it becomes light and therefore rises. The ascending warm air expands and cools as it rises. And if sufficient moisture is present and the cooling process proceeds sufficiently, precipitation is formed.

The preceding discussions of cyclonic and convectional storm types describe how warm, moist air was lifted and cooled to the precipitation point by a process of circulation. In the first instance, warm air was lifted over heavier cold air; in the second instance uneven heating caused air to rise.

THE OROGRAPHIC, OR MOUNTAIN, TYPE is the third familiar storm type that causes precipitation. A mountain range can act as the wedge or barrier over which warm, moist air is lifted and cooled to the point where precipitation occurs. Here the warm-air movement may be related either to the general circulation within the atmosphere or to the circulation about a storm center.

The best example of orographic precipitation in this country is along the West Coast Ranges in Washington, Oregon, and California. Moist air, flowing in from the Pacific, is lifted in its general eastward movement, and a zone of normally heavy rainfall results. Orographic precipitation is generally of a low intensity, but because the mountains are fixed in one location, the resulting precipitation falls on the same general location and the annual rainfall is high. That is in contrast to the precipitation from storms that are free to move and occur in many different locations.

Variations of the three basic storm types occur, and their effects sometimes may be combined. For example,

thunderstorms are more commonplace in the mountains where some preliminary orographic lifting has taken place and has increased the instability of the air and the likelihood that thunderstorms will form. Frequently the rainfall resulting from cyclonic storms is accentuated by the orographic lifting of a mountain. Another example of combination of storm types is the occurrence of thunderstorms in the unstable warm sector or with the passage of a cold front in a cyclonic storm.

Thus far we have dealt with the moisture sources, atmospheric circulation, and some of the more important processes by which moist air is lifted. When the lifting and cooling process proceeds to the point of atmospheric condensation, then small droplets are formed. The condensation takes place on dust particles in the air. As droplets, the moisture is in the form of a cloud or fog, and may remain suspended if there is any upward movement of the air to support it. In fact, it is commonplace for droplets to reevaporate without producing any precipitation. Under a number of conditions, however, the droplets will grow to sufficient size and weight to fall. The increase in size is thought to occur in two main ways. The first is in clouds, which are a mixture of ice and water particles, cooled below the freezing point. Because of differences in vapor pressure, the water droplets evaporate while condensation takes place on the ice particles. The process continues until the particles can no longer be supported by the updraft of air. They may collide when they fall and combine then to form even larger drops. Another condition under which raindrops form is when warm and cold droplets are mixed within a cloud. Again, by differences in vapor pressure, the warm droplets evaporate, and the cold ones grow in size and weight.

When raindrops are frozen while falling through cold air (as may happen below a warm front) sleet or ice pellets are formed. They differ from hail, which occurs almost exclusively in violent thunderstorms. Hailstones are composed of layers built up as a result of repeated ascents and descents or in dropping through a turbulent air mass; the stone grows larger each time a layer of moisture is condensed and then frozen on its surface. Snow—the other common form of precipitation—represents crystals and combination of crystals as flakes, which are formed when condensation takes place below freezing temperatures.

Water is delivered to the land in many forms—such as rain, hail, snow, and sleet. Its subsequent movement depends on its form of delivery and on the character of the plants, soil, and underlying material receiving it. What happens to water after its delivery to the land determines to a significant degree the severity of floods and erosion, the quantity and quality of water supplies, and the production of crops.

Vegetation will interpose leaves, branches, and litter as barriers to rain and snow, so that only a part of the precipitation reaches the soil beneath without interference. Vegetation thus affects both the quantity and distribution of precipitation that reaches the soil surface. Rain and snow are affected differently in some respects by vegetation. Part of each passes through the canopy of vegetation without being caught, but if the canopy is dense the larger part strikes leaves or branches.

Of the part thus intercepted some spills from drip points, some flows to the ground along stems, and some is held and later evaporates. Rain wets the surface it strikes. It can form only a thin water layer before it starts flowing toward the ground.

Snow may wet the surfaces it strikes, but whether it does or not, it can pile to a considerable thickness upon them. A good deal more snow than rain can thus be held by vegetation. Snow is released from vegetation by sliding—often triggered by wind—and by melt. Often in forests there is abundant evidence of both, visible in peaked snow ridges around tree crowns and snow

pitted by water drops beneath them.

The quantity of precipitation intercepted by vegetation and then evaporated varies, depending on the kind and size of storm and the kind of vegetation. It represents, however, a fairly constant percentage of annual precipitation under the same vegetation conditions. In various places where it has been measured, interception loss is generally between 5 and 15 percent of the annual rainfall.

Water losses caused by interception can be reduced by thinning or changing the vegetation, so as to lessen the volume of the canopy. If the thinning or other change does not lower seriously the soil protection provided by the vegetation, some additional water may thus be delivered to the ground without damaging consequences.

In the Rocky Mountains of Colorado, for example, snow accumulation on the ground was increased the equivalent of 2 inches of water by removal of all merchantable timber from a forest of lodgepole pine. No adverse effects—such as overland water flow or erosion—followed the cutting, because summer rains were light and winter storms brought only snow. But interception loss cannot always be reduced with impunity. Some loss of this kind is inevitable if the soil is to be protected from the impact of rain.

Rain that reaches the soil surface is wholly or partly absorbed by the soil in the process of infiltration. How much of it enters the soil depends upon the rate of rainfall and the receptiveness or infiltration rate of the soil. When the rainfall rate exceeds the infiltration rate, the excess rain becomes surface flow, which runs off quickly to streams. Surface flow is undesirable because it may erode the soil and also because it often produces damagingly rapid and high flows in streams during storms.

Erosion of cultivated land is the result of water delivered to the soil at a rate higher than the infiltration rate of the soil. Because of the damaging consequences of surface-flowing water, many land management practices are designed to induce as high an infiltration rate as possible.

Infiltration rate is determined by a combination of factors—some natural to the soil, some the result of activities related to land use. Infiltration rate is naturally greater in sandy soil than in clay. Ordinarily the finer the soil texture, the lower the rate of infiltration. But the effect of texture is modified greatly by the aggregation, or arrangement, of the soil particles and by soil structure beneath the surface.

The effects of structure upon infiltration rate show themselves near the soil surface and down through the profile. A surface soil that is well supplied with organic matter is ordinarily far more receptive to water than a soil consisting mainly of mineral material. Maintenance of an organic-reinforced open structure is one of the objectives of stubble-mulching and other farming practices that mix plant residues into the soil. The plowsole, a layer of compacted soil common in some long-cultivated fields, impedes downward waterflow and thus reduces infiltration at the surface.

Water from snowmelt is not different from water supplied by rain, after it has entered the soil. It is different, however, in the way it is delivered to the soil. Water draining from the base of a snow blanket flows to the soil surface; it does not have the impact force of raindrops. Bare soil, therefore, is not damaged by snowmelt delivered to its surface. Snow cover frequently protects the soil from freezing and therefore maintains a higher infiltration rate. Except for this, the effects of land treatment and soil are the same on the infiltration of snow water and rain.

Snow is singularly subject to change as it lies on the ground. To some extent man can control the quantity, time, and rate of water release from the snow pack to the soil. Snow drifts before the wind while it is being laid upon the ground and later before it packs. Drift-

ing is caused by windbreaks, which produce a local drop in wind velocity. They collect snow some distance to leeward and a lesser distance to windward. That is why snow fences are used along roads in snowy lands. Erected parallel to the roads, they reduce the amount of snow on the roads by causing part of it to pile up near the fences.

An exploratory investigation in Utah demonstrated the possibility of retarding snowmelt in windswept mountain lands by causing snow to drift. Snow fences were built at right angles to the prevailing direction of winter winds. The snow accumulating in the lee of the fences was deeper than that in undrifted places nearby. When all the undrifted snow had melted, within the drifts there remained 15 inches of water as snow. The drifts released their water to the soil over a longer period than did the undrifted snow, and thus contributed water to the soil and to the streams later in the spring and summer. Thus, where wind drifts the snow, it may be possible to reduce the high spring flow of streams and to increase lower flows later in the year.

Snow lying on the ground is subject to melting and sublimation, which is the transformation from a solid to a vapor. Melt rate is influenced by the amount of heat reaching the snow. The source of the heat is the sun. But besides heat received directly from the sun, snow also receives heat from the soil beneath, from heated objects such as trees, above, and from warm air that passes over it. If snow on the ground is shaded by trees or other cover, some of the sun's heat is intercepted, and the snow melts more slowly than if it is fully exposed to the sun. At first glance this suggests that a dense forest would be more desirable than an open one to prolong the melting of snow. But the matter is not so simple. More snow is intercepted by the crowns, and, generally, less snow accumulates on the ground as forest density increases. Probably for maximum control over water yield from snow, some condition less than a full forest cover is needed. The condition desired is one in which the greatest delivery of snow to the ground is coupled with the greatest amount of shade. Obviously such a condition represents a compromise between increasing snow accumulation and decreasing shade found as the forest is cut more and more heavily.

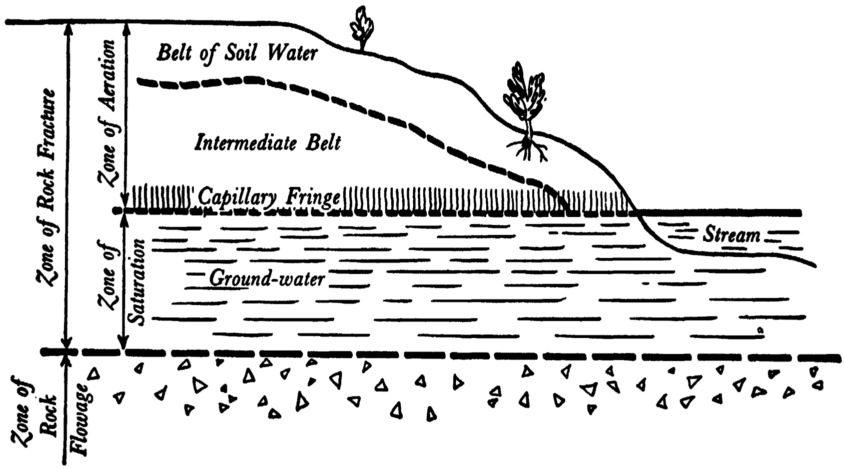
Water evaporates from the snowpack, and the solid ice crystals themselves sublime. Whenever the vapor pressure of the air above the snow is less than that at the snow surface, water evaporates from the snow. When the dewpoint is below the freezing temperature, water condenses on the snow. Thus as snow lies on the ground it may lose water to the air or receive water from it. Evaporative loss of water from snow varies from place to place and from season to season. Near the Rocky Mountain crest in Colorado, for example, 0.24 inch of water was lost from the snowpack in an open space during the winter, and 1.99 inch during the melting period in spring. In the Sierra Nevada of California, by way of contrast, evaporative losses in a large forest opening totaled 0.75 inch from December to March and 0.69 inch from April to May.

Water that has entered the soil either increases the moisture content of the soil or drains through it. If the soil is dry, the water entering wets successively deeper layers to field capacity, which is the moisture content to which each layer must be raised before water can drain through it. When the entire profile has been wet to field capacity, the additional water entering the soil drains into the underground, later emerging in springs and seeping into streams, or adding to subsurface supplies in valleys.

Water draining through the soil feeds streams longer and more evenly than water flowing over the soil. Hence for crop production of all kinds and for maximum control over water yield, the best land-use practices are those that induce the most water to enter the soil.

Water held within the soil after drainage has ceased can be transpired

Ground-water Zones and Belts



by plants or lost by evaporation. Plants cannot utilize all water stored in the soil; they can dry the soil only to the wilting point, a moisture content at which the force holding water to the soil particles equals the maximum water-absorbing force of plant roots. Just as clay soils can hold more water at field capacity than sands, so also is the wilting point of a clay higher than that of a sand. Both the upper and lower limits of the available moisture range, between wilting point and field capacity, are determined primarily by soil texture. Little can be done by cultural practices to increase this range.

Evaporation can dry soil below the wilting point. In the process the soil dries from the surface downward, for all soil water lost by evaporation must rise to the soil surface and pass through it. Ordinarily evaporation dries the soil most within the surface foot. But given sufficient time without water additions, soil may dry many feet deep by this process alone.

Evaporation and transpiration together take a toll of soil water in response to a number of conditions. If the soil surface is free of plants and thickly covered with an insulating layer of litter, evaporative loss will be much less than if the vegetation-free soil is bare. A deep soil loses less water under a cover of shallow-rooted plants than under plants whose roots reach to the full depth of the soil. Deep soils fully permeated with roots lose more water than shallow soils similarly permeated. Where a water table exists within or a short distance below the root zone, the lower soil layers may not dry perceptibly, although large quantities of water may be withdrawn from the standing water.

Evapotranspiration can be reduced in various ways. Protective mulches can be laid on the soil surface to reduce evaporation. Weeds can be removed from cropped lands by cultivation or killed by other means. Vegetation can be thinned, and, under some climatic conditions, evapotranspiration can be reduced as a consequence. Shallow-rooted plants can be grown on deep soil previously occupied by plants with deep roots. There are, however, limitations to how far evaporative losses can be reduced. It is obviously not desirable to reduce the density of plant cover so much that the soil is insufficiently protected against storm runoff

and erosion. Production of certain crops requires irrigation, dense planting, or other practices that favor high water use. And if the dry season is long and severe, changing the plant cover may have little effect upon water loss.

Perhaps the most important point to make regarding evapotranspiration is that it is a natural process that occurs wherever there is vegetation. While evapotranspiration and other evaporative water losses can sometimes be reduced by treatments given the soil and its cover, they cannot be eliminated.

Water that infiltrates into the soil is known as subsurface water. It may be evaporated from the soil; it may be absorbed by the plant roots and then transpired; or it may percolate downward to ground-water reservoirs. Subsurface water occurs in a zone between the ground surface and the lower limits of porous, water-bearing rock formations. This zone is designated as the zone of rock fracture, and is subdivided into the zone of aeration and the zone of saturation.

THE ZONE OF AERATION is divided into three belts—the belt of soil water, the intermediate belt, and the capillary fringe. The belts vary in depth and are not sharply defined by physical changes in the soil. Generally a gradual transition exists from one belt to another. In considering the movement of water through the soil profile, however, it is desirable to delineate zones or belts that have different effects on the subsurface movement of water.

The upper belt, or belt of soil water, consists of the topsoil and subsoil from which water is returned to the atmosphere by evaporation from the soil and transpiration of plants. As water passes through the surface and enters the belt, it is acted upon by gravity and molecular attraction. Gravity tends to pull the water downward. Molecular attraction tends to hold the water in a thin film over the particles and in the very minute spaces between the soil particles. Only when sufficient water has entered this belt to satisfy the storage requirements due to molecular attraction does water start to percolate downward under the force of gravity. Water in this belt is of particular importance to agriculture because it furnishes the supply for all vegetative growth. Water passing downward from the belt is beyond the reach of plant roots and is no longer available to support plant growth. The depth of the belt of soil water varies with the soil type and the vegetation and may vary in depth from a few feet to 50 feet.

Water passing through the belt of soil water enters the intermediate belt and continues its movement downward by gravitational action. Like the belt of soil water, the intermediate belt holds suspended water by molecular attraction. In this belt, however, suspended water can be considered dead storage since it is not available for use. In the hydrologic cycle, this belt serves only to provide a passage for water from the belt of soil water to the capillary fringe. The intermediate belt may vary in thickness from zero to several hundred feet; the thickness has a significant effect on the time it takes water to pass through the belt.

The capillary fringe lies immediately below the intermediate belt and above the zone of saturation. It contains water that is held above the zone of saturation by capillary force. The amount of water held and the thickness of the capillary fringe depend on the type of material in which the capillary fringe is located. In silty material it may extend 2 feet or more above the zone of saturation. In a coarse, gravelly material it may extend less than an inch. As in the intermediate zone, water is stored in the capillary fringe. In the hydrologic cycle, however, it also provides a passage for water being moved by gravity from the surface to the zone of saturation.

The zone of saturation, or ground water, forms a huge natural reservoir that feeds springs, streams, and wells. Water moving by gravity through the

Water can be majestic

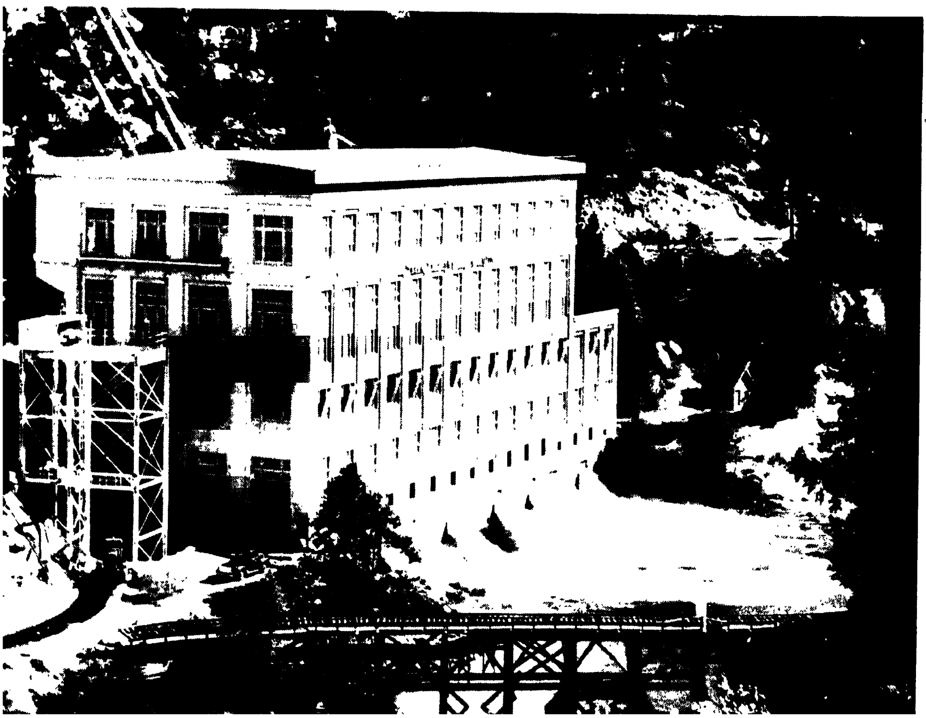
and happy;

pleasant,

life-giving and purifying;

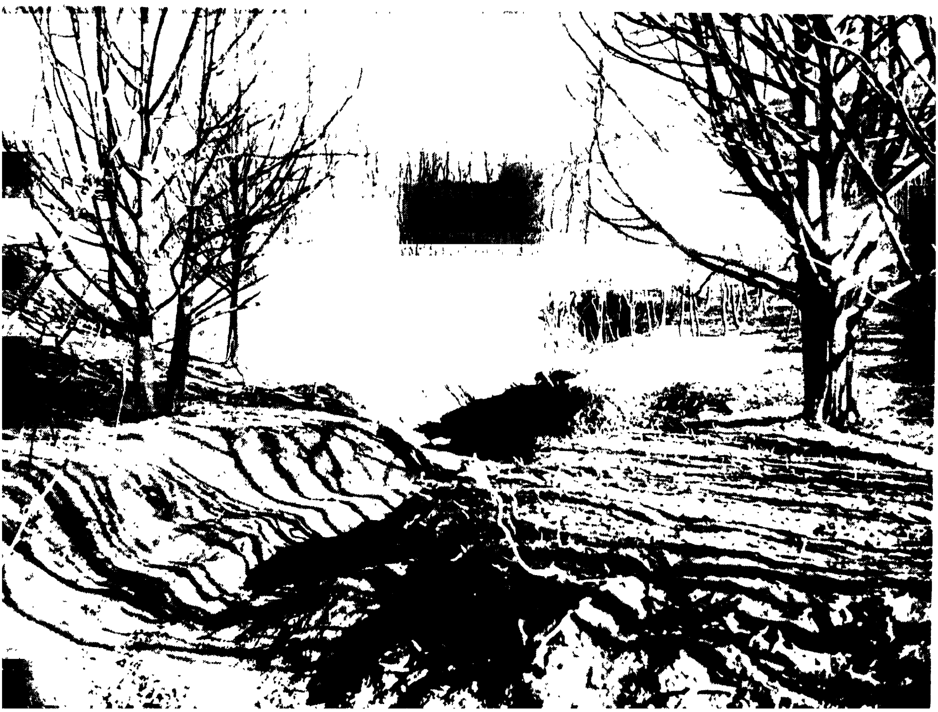
productive

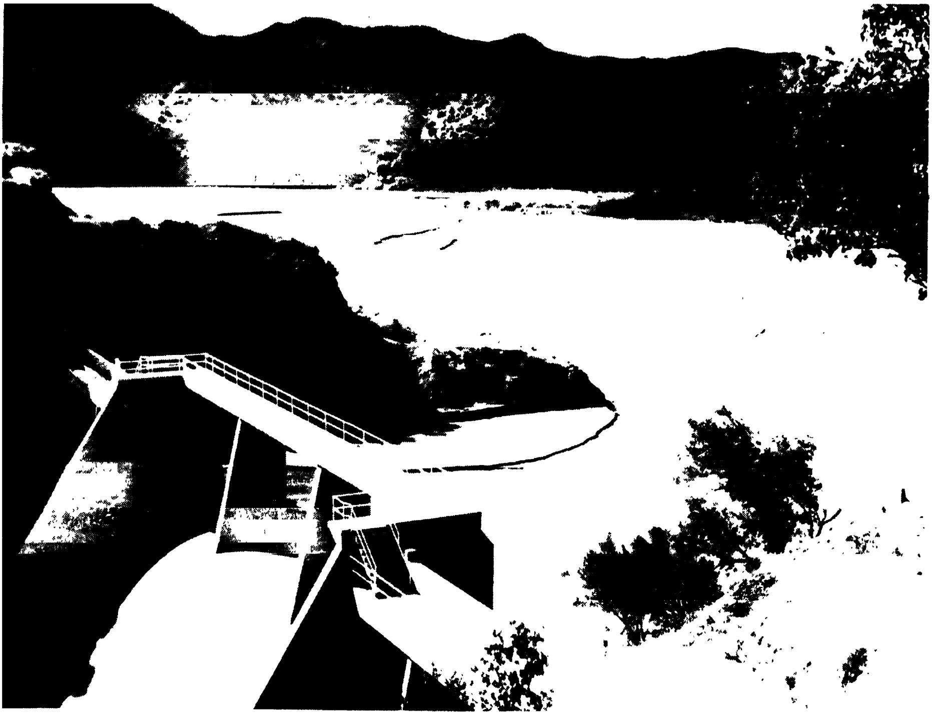
and powerful.



But to insure all that, we must guard our watersheds against excessive use

and wildfire



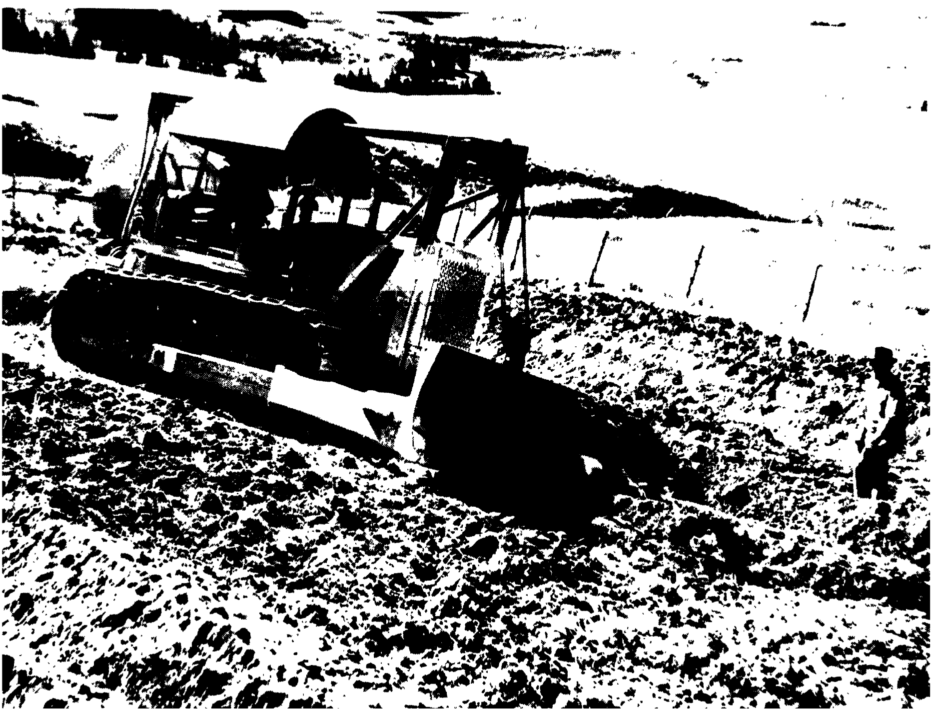


—against other types of mismanagement that fill up reservoirs with silt

or lead to flash floods, which endanger cities.

We can rebuild damaged watersheds by plowing furrows to slow down storm runoff,

by bulldozing cross dams to hold the water;



by planting grass

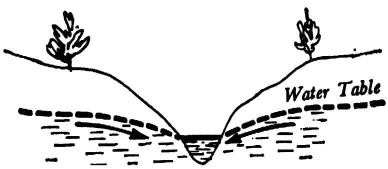
and trees, and by using other conservation methods, which we stress in this book.

So the choice is ours: Gullies, which waste our substance,

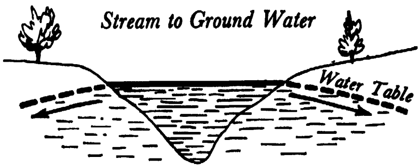
or pleasant, productive, useful water—water under control.

Seepage

Ground Water to Stream



Stream to Ground Water



belts of the zone of aeration enters the upper surface of the zone of saturation, which is referred to as the water table. All the pores and spaces in this zone are filled with water. The depth of the zone depends on the local geology. It may include loose, unconsolidated deposits of sand and gravel, as well as porous rock formations such as sandstone and limestone. Its lower limit is that point where the rock formation becomes so dense that water cannot penetrate it. The zone may vary in depth from a few feet to hundreds of feet, and instances are known where porous rock has been found at depths of more than a mile.

The zone of saturation is extremely important, because it provides the supply for all our wells and the normal, relatively uniform flow of our streams. It acts much the same as a surface reservoir, receiving water during wet periods, which raises the water table on the upper surface of the zone as water drains into it from above. It can thus store huge supplies of water which, because of the slowness of movement through the zone, is discharged at a relatively uniform rate.

The action of gravity tends to make the surface of the zone of saturation or the water table a level surface. As the movement of water is relatively slow through the soil and rock formations, however, the frequent additions and withdrawals do not usually permit the water table to become a level surface.

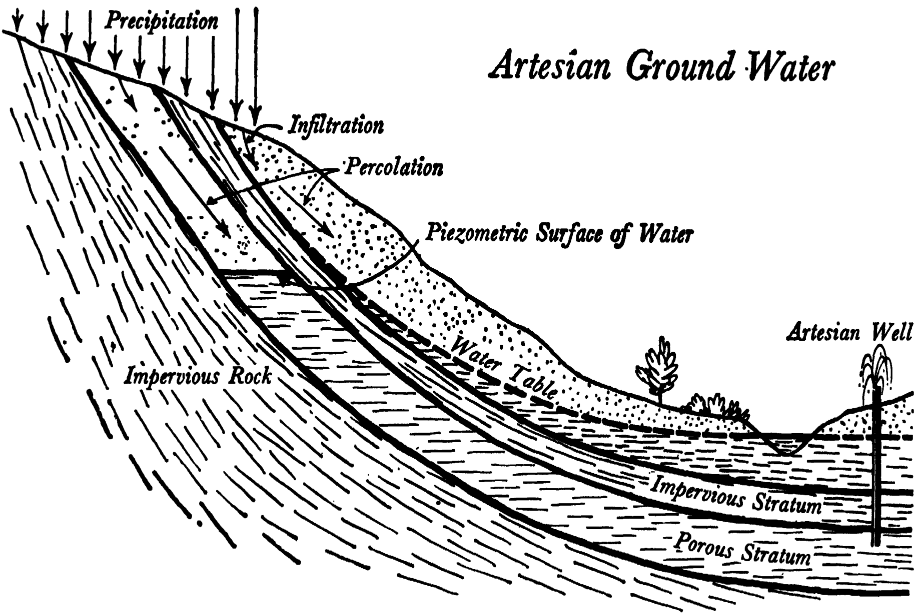
During periods of low flow, the level of the water surface in a stream may drop below the level of the water table. Ground water will then seep into the stream and the level of the water table will dip toward the stream in the direction of ground-water flow. When the stream is flowing for periods at a level above the water table, seepage will take place in the opposite direction and tend to raise the water table. Because of the constant changes resulting from increased supply to ground water or the increased demand from ground water, the level of the water table is constantly changing.

Geologic formations also cause variations in the water table. Where impervious layers of material occur, it is possible to have two or more water tables at different elevations or to have water confined below an impervious layer under hydrostatic pressure, which is pressure caused by the weight of water above. Sufficient pressure occasionally occurs to cause the water to rise in a well above the land surface, creating a flowing or artesian well.

Many varying conditions occur as a result of different geologic formations, but in the hydrologic cycle the principal functions of the ground water zones are as follows:

1. Zone of aeration—receives and holds water for plant use in the belt of soil water and allows the downward movement of excess water.
2. Zone of saturation—receives and stores, and provides a natural regulated discharge of water to wells, springs, and streams.

Runoff occurs when precipitation that does not have an opportunity to infiltrate into the soil flows across the land surface; eventually most of it enters stream channels which carry it



to the ocean. A part of the precipitation that infiltrates the soil percolates downward to the water table and also enters stream channels through springs or seeps. Broadly speaking, runoff is composed of water from both surface flow and seepage flow. It is an extremely important segment of the hydrologic cycle, since, on the average, about 20 percent of all precipitation is carried to the ocean by streams and rivers.

Much of our agricultural and industrial development is directly concerned with this water. Irrigation, waterpower developments, domestic and industrial water supply, water transportation, and sewage disposal depend more or less on streamflow. In order to utilize this resource to the fullest extent and also to avoid disastrous effects during periods of high flow, it is necessary to understand the factors which affect the volume and rate of flow so that estimates can be made that will assure sound future development.

The amount and the rate of precipitation affect the volume and peak flow of a stream. Although man as yet has no positive control over precipitation, estimates of water yield can be made to permit proper allowances in developments utilizing streamflow. Similarly, temperature may influence runoff. During periods of low temperatures, precipitation may accumulate in northern areas in the form of snow. Rapid temperature rises, particularly when the soil is frozen, often result in exceedingly high surface runoff.

The physical characteristics of a watershed indicate what might be expected in the way of the total volume and the peak rate of runoff. A relatively impervious, steeply sloping watershed may shed most of the precipitation falling on it, but a watershed with good permeable soil that is properly protected may permit a high percentage of the precipitation to be infiltrated into the soil.

In the first instance, high volumes and peak rates of flow would be expected, while in the latter case the peak flow would be considerably less, although the volume produced over a long period would not be reduced significantly. Steep slopes produce high peak rates of runoff but have little

effect on the volume of runoff. A good vegetative cover and a well-maintained soil can materially reduce the rate at which water reaches the stream channels. It not only retards surface flow, but also increases the volume passing through the soil and entering the stream as seepage flow.

Lakes, ponds, swamps, and reservoirs also act to level off peak rates of flow in the stream reaches below. Generally, there is but little loss of flow to ground water in natural lakes and swamps since they usually exist because there is little or no percolation into the soil.

Among the many other factors that affect runoff in varying degrees are barometric pressure, which can affect the flow of springs and artesian wells; seepage from stream channels; and evaporation from streams. The degree to which such factors must be considered depends on the particular problem being studied. No two streams or watersheds are alike. Each has its own characteristics.

Although the amount of water with which we are concerned in the hydrologic cycle remains essentially constant, its distribution and occurrence are continually changing. Water is a rather unique natural resource, since it may be utilized to the fullest extent by man, processed by Nature, and returned to man through the never-ending hydrologic cycle.

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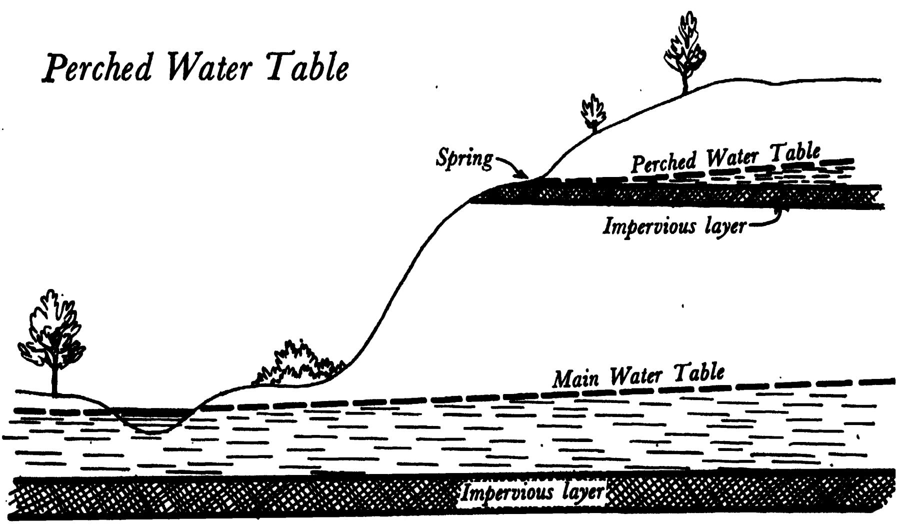
Perched Water Table



The Water in the Rivers and Creeks

W. B. Langbein and J. V. B. Wells

The rivers and creeks of the Nation are the major source of our water supply—75 percent of the water used by the cities and towns and by farmers for irrigation, 90 percent of the fresh water used by industry, and nearly all the water used to generate hydroelectric power.

Dams and reservoirs have become prominent features of the American landscape. They store and save floodwater until it is needed by cities and for irrigation, power, and navigation. The capacity of the reservoirs in 1955 was more than 278 million acre-feet, enough to store about 20 percent of the average annual yield of the rivers and creeks in the United States.

Surface water, the water on the surface of the land, represents the drainage from the land. We see it in flowing rivers and creeks, and in lakes and ponds. Surface flow is derived partly from the rainfall that is shed into the watercourses from the sloping lands. A part of the rainfall in storms that is absorbed by the soil also becomes surface water by its discharge as wet-weather seeps into rills and runnels. These are the direct runoff components that produce the flood rises in the streams.

The part of the rain or the snowmelt that penetrates deeply becomes ground water recharge and is discharged to the streams slowly. The ground-water effluent becomes the base flow that maintains streams in fair weather.

When we speak of surface water we mean streamflow—regardless of its source. Lakes and reservoirs may be viewed as streamflow in storage. We also speak of streamflow as the flow in natural channels even though the flow has been regulated. But when we wish to discuss the flow in a natural state, the term "runoff" is in common usage to describe the water drained from the land through the rivers and creeks.

Not all precipitation is drained from the land. The precipitation that wets the soil and vegetation is dried up soon after each rain and is never available for runoff. Some of it is stored in the ground, from which it serves the needs of vegetation. Direct evaporation and the transpiration of vegetation exert a sort of prior claim on the precipitation. The runoff is only a remainder over and above the assessment levied by the evapotranspiration processes; as such, it varies to a greater extent than precipitation. Thus a twofold variation in precipitation either from one year to another or from one place to another may result in a fourfold variation in the amount of runoff.

The drainage or catchment area is the hydrologic unit used for comparing streamflow data. The streamflow rates usually are measured in terms of cubic feet per second. Volumes of flow for given periods of time generally are reported in terms of acre-feet. For comparisons between different streams it is convenient to express the figures in terms of the drainage area—rates in cubic feet per second per square mile or volumes in inches of depth. The runoff in inches is the depth to which an area would be covered if all the water draining from it in one given period were uniformly distributed on its surface. The term is particularly useful for comparing runoff with rainfall, which also is usually expressed in inches. Streamflow is the only part of the hydrologic cycle in which water is so confined as to make direct measurement possible. All other measurements in the hydrologic cycle, like rainfall and soil moisture, at best are only inadequate samples of the whole.

Observations of streamflow are made regularly by the Geological Survey at about 6,500 gaging stations located on all principal rivers and a large number of their tributaries. The network of gaging stations covers all States, but the density of coverage tends to reflect

the value or volume of water, so that there are broad areas (chiefly in the West) and small streams (in all parts of the country) where the number of gaging stations is inadequate to give a satisfactory description of the occurrence of runoff.

Because of the erratic occurrence of floods and droughts, which are key factors in the design of water development projects, the maintenance of continuous and routine observations is essential if one is to be ready when such extremes occur. Information collected at the stations is published by the Geological Survey in a series of water-supply papers. Those papers present annually the daily mean discharges of the river at the measurement station and the extreme high and low discharges in each year.

STREAM GAGING is simple in principle but the diverse details encountered and the need for undivided attention make it a field for specialists.

Operations at a river-measurement station consist of two equal parts—obtaining a record of stage, called the gage-height record; and using the current meter to define the relation of stage to discharge, called the stage-discharge relation.

A gage-height record may be obtained by means of periodic (such as twice daily or daily) readings of a gage or by means of an automatic water-stage recorder, which furnishes a continuous graphic record of the stage.

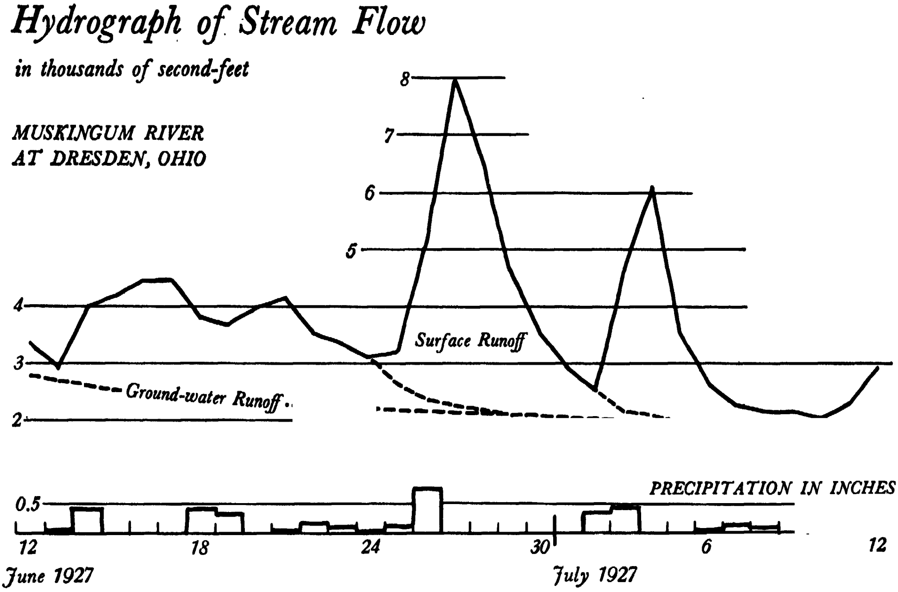
Gages that are read periodically by an observer differ in their construction. Some, known as staff gages, consist of a graduated scale attached to a bridge pier or along the river bank in such a position that the height of the water surface can be read directly on the scale. The scale is generally graduated in feet and tenths of a foot. Other types of nonrecording gages consist of weights suspended by wire or chain and lowered from a bridge until the bottom of the weight touches the river surface. A scale is provided so that the height of the river surface can be read directly, corresponding to the position of the bottom of the weight.

Recording gages are generally enclosed within a shelter built over a stilling well. The stilling well is built along the riverbank or attached to a bridge pier and is connected with the river itself by a pipe, called the intake, so that the water surface in the well is the same as that outside.

The recording instrument consists of two elements—the clockwork, designed in most instruments to move the recording paper at a constant predetermined rate (commonly 2.4 inches a day), and the float and float cable, designed to move a pen or pencil across the chart, in a direction perpendicular to the paper travel produced by the clockwork and in an amount proportional to the raising or lowering of the float produced by the fluctuations of the water level in the well.

The translation of the record of stage into one of discharge is done by means of the stage-discharge relation. At some point along a stream a given rate of flow is closely associated with a given stage, and at such a point a fixed stage-discharge relation may be said to exist. The river configuration that fixed this relation is called the control. The relation is defined by using the current meter to measure the rate of flow at a number of river stages. Generally an attempt is made to make sufficient measurements to include the lowest and highest stages experienced as well as intermediate stages. The results of the measurements are plotted against the stage prevailing during the measurement to define the rating curve for the station.

ONLY IN EXCEPTIONAL locations does the rating curve remain fixed. The action of flowing water, particularly during floods, and the action of ice on the river bed and sides change the hydraulic properties of the river channel and produce corresponding changes in this relation. Consequently frequent measurements are made at each gaging station to detect changes in the rating



or to confirm its constancy if no changes have occurred.

In most rivers the low-water part of the rating (low-water control) is affected by minor or local changes in the bed, whereas the high-water parts remain relatively fixed. The high-water controls consist of the whole channel and flood plain over a considerable reach or a large structure such as a bridge, whose general configuration and dimensions are not seriously affected by any except the most extraordinary floods. When the discharge measurements disclose that a change has occurred, a new rating curve is plotted.

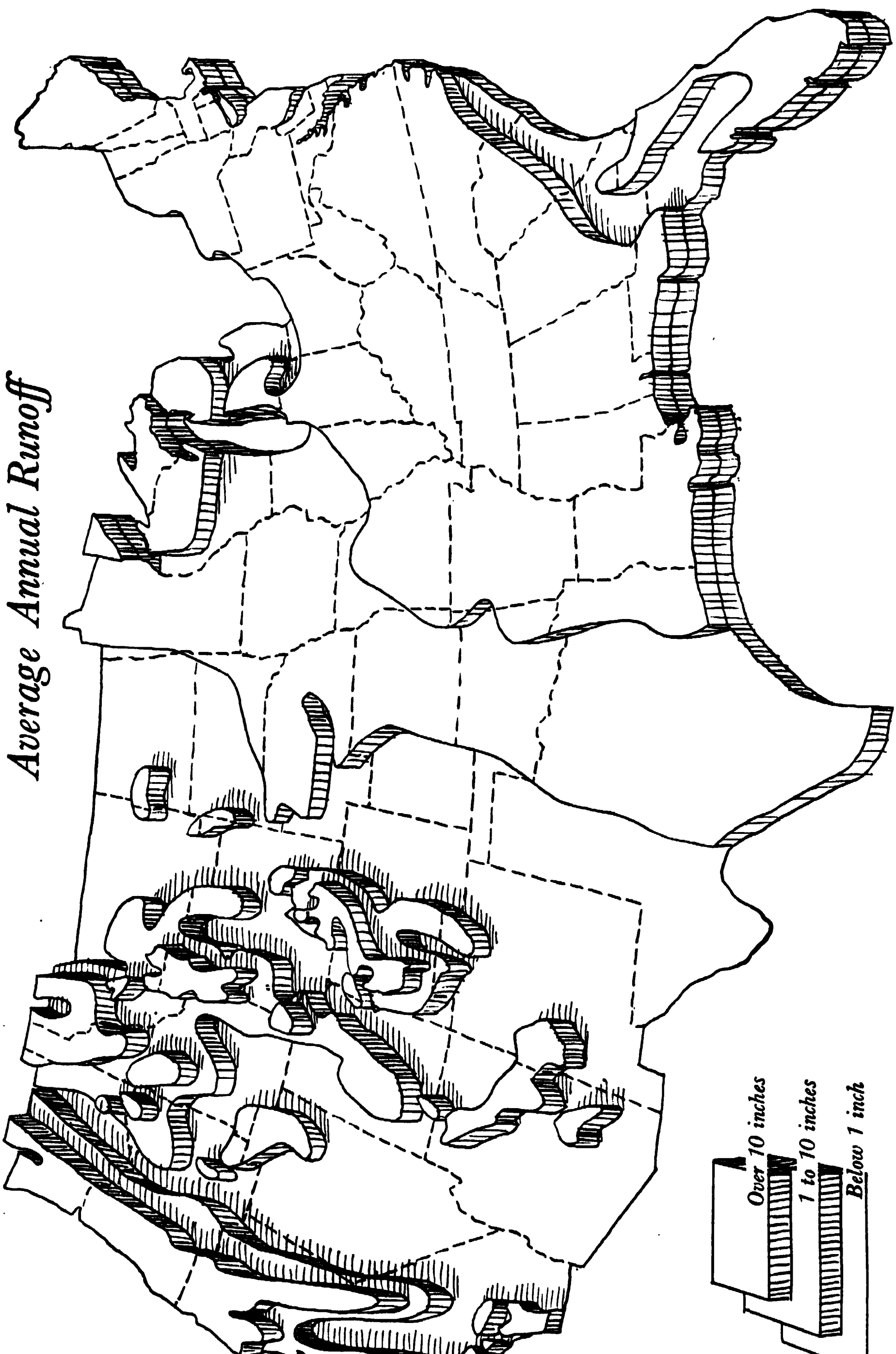
Measurements of discharge are made by the current meter, of which the earliest applications go back to 1790. There are two general designs—the propeller-blade type and the cup type. The propeller type is in general use in continental Europe, but in the United States, Canada, and Great Britain the cup-type meter is standard. The rotation of the meter is due to the difference in pressure by the moving water on opposite sides of the cups. The cups rotate at a rate proportional to the velocity of the water.

The modern meter embodies in its design the experience of many years by men in the Geological Survey and others. It will measure velocities from 0.2 to 20 feet a second. It is rugged and easily dismantled for cleaning. It maintains its calibration under rough treatment accorded it by flood. It can be used in turbid water without damage from silt.

The discharge of a stream is equal to the product of its cross-sectional area and its mean velocity. Thus, when one makes a discharge measurement, the cross-sectional area of the river is also measured. That is done by sounding the depth of the stream at measured intervals across the stream from one bank to the opposite bank.

Discharge measurements are made in several ways. During low stages, the rivers can often be waded. At flood stages, the meter is suspended from a cable, and the measurement is made from a bridge or a car run on a special cableway.

During floods, measuring conditions are encountered that tax the ingenuity of the engineer. Rivers are deep and the water moves swiftly. Velocities of 20 feet a second (13.5 miles an hour)



Average Annual Runoff

and depths of 50 feet or more have been encountered. Special equipment is necessary to permit measuring under such conditions. Heavy sounding weights of 100 or 200 pounds (300 pounds on the Mississippi River at Vicksburg) are used with specially designed portable cranes for raising and lowering them.

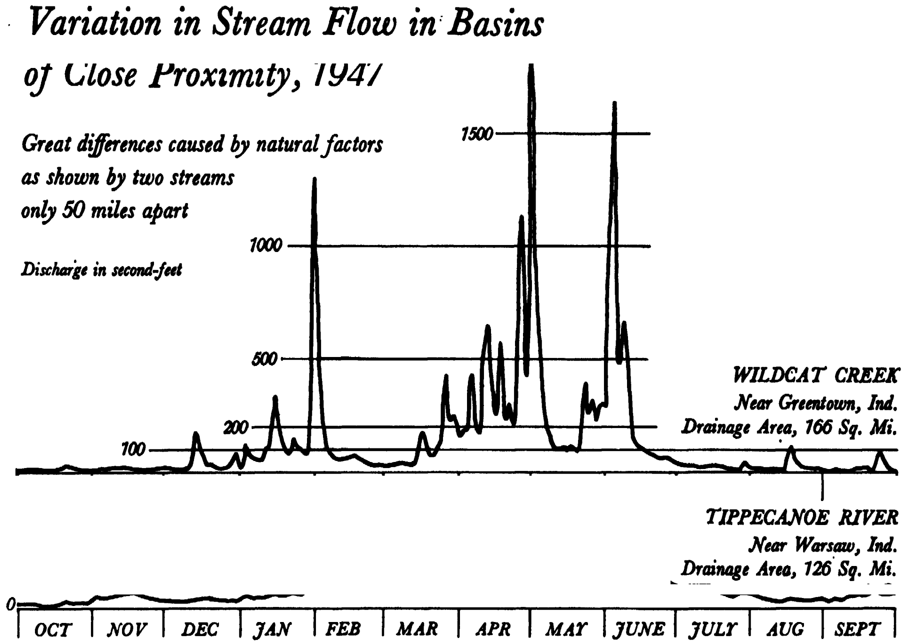
But even with this special equipment, measurements of the discharge of rivers in flood are not easy to get. Many of the smaller streams rise and fall so rapidly that the flood may be over before the engineer can get to the gaging station. Then, too, only rarely is one stream alone in flood; more likely all streams in the surrounding region are also flowing at high rates. The floods do not continue long enough for the engineers to measure them all. Road washouts may prevent an engineer from reaching a station at all. Even if he did arrive when a flood was at its peak, the swollen stream might be carrying so much floating debris that a current meter would be torn away. Or perhaps the cableway or bridge from which the measurements are made has been destroyed. Despite the brave exertions of the stream gagers, consequently, current-meter measurements of all floods cannot be obtained. Engineers have therefore devised indirect methods of computing the discharge of the stream at its peak.

The foremost of the indirect determinations is known as the slope-area method. The downstream flow of a stream is retarded by friction. During steady flow in a uniform channel, there is a balance between the force of gravity and the retarding force of friction; otherwise the flow would tend to accelerate in accordance with the law of freely falling bodies.

By experiments and practice, the Manning formula has been found to be the most practical and simplest relationship for the velocity of a stream: Mean velocity is a product of friction, depth, and slope. Therefore, if soon after a flood has passed, the engineer can survey a suitable reach to determine such things as the width, transverse area, mean depth, and the slope of the water surface, he can estimate its mean velocity. The friction, or roughness, coefficients are selected according to the condition of the channel. Values of the coefficients vary relatively little compared to other hydraulic factors and are now quite well established as a result of considerable experience. The trained hydraulic engineer has little difficulty in establishing a reasonable roughness coefficient for each channel condition. From the computed value of the mean velocity, the discharge follows simply as the product with the transverse area of the stream.

ANNUAL RUNOFF in the United States ranges from more than 80 inches in the "rain forest" of the Olympic Mountains in Washington to less than one-fourth inch in the Arizona deserts. Runoff is fairly uniform throughout the humid east but is extremely diverse in the West. A marked feature in the countrywide distribution of runoff is the east-west transition over the Great Plains. These broad features generally reflect the climatic pattern of the country. Precipitation as the source of the streamflow sets an upper limit to its amount. But the climatic factors associated with temperature controls the amount of the precipitation that is lost by evapotranspiration. The higher the temperature, the greater the loss. Thus an annual precipitation of 20 inches will result in more runoff in a region where the annual temperature is 50° F. than in one where the temperature averages 70°.

FEATURES OF THE TERRAIN also affect the amount and distribution of runoff. Relief of the land exerts prominent influence on the occurrence of runoff. The isograms shown in the chart outline the western mountains. The well-known increase in rainfall and accompanying decrease in temperature with altitude produces a marked increase in runoff from the higher mountain zones. The hydrologic nature of a drainage



basin is reflected in the behavior of the stream-flow; the most sensitive characteristic is its timing—that is, the time within which the runoff from a storm is discharged from the basin.

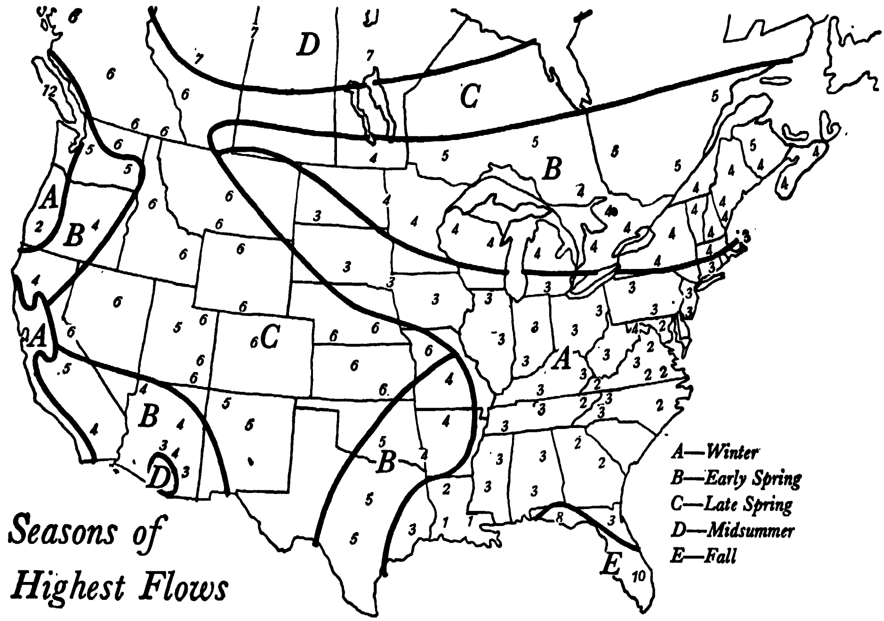
In some basins the soil mantle and underlying rocks have a large capacity for the penetration and storage of ground water, which is released to the streams at a relatively steady rate.

The streamflow, in consequence, may be well-sustained during the fair-weather periods. But on the other hand, the streamflow from basins with a shallow soil mantle upon impermeable rocks or hardpan may recede rapidly from sharply concentrated flood peaks to low flow or even no flow, between storms. Except under extreme conditions, however, ground storage and timing factors appear to influence the total volume of runoff only slightly.

Striking effects in the runoff characteristics of differences in underground storage capacity may be noted in the accompanying hydrographs of two basins near each other in Indiana. The basin of Wildcat Creek is underlain by relatively impermeable glacial drift that has a low rate of intake and a low storage capacity. The basin of Tippecanoe River contains several lakes and is underlain by thick, permeable glacial deposits capable of absorbing, storing, and paying out water remarkably evenly. The flow of Tippecanoe River is largely base runoff.

THE MAJOR EFFECT of geology on annual runoff appears to be twofold.

First is the effect on evapotranspiration, which is in general determined by climate. Certain local conditions favor the loss of water; in other places, local physical conditions are such as to protect the water in the ground from loss during the delay between precipitation and runoff. A permeable soil or mantle rock may absorb rainfall so easily and permit it to percolate to such depths that the stored water is effectively insulated from evaporation and transpiration. The water then reaches the water table and eventually discharges into the streams. An outstanding example of this effect is found



in the sandhills of Nebraska. A somewhat similar situation exists on Long Island, where, however, the ground water flows directly to the sea.

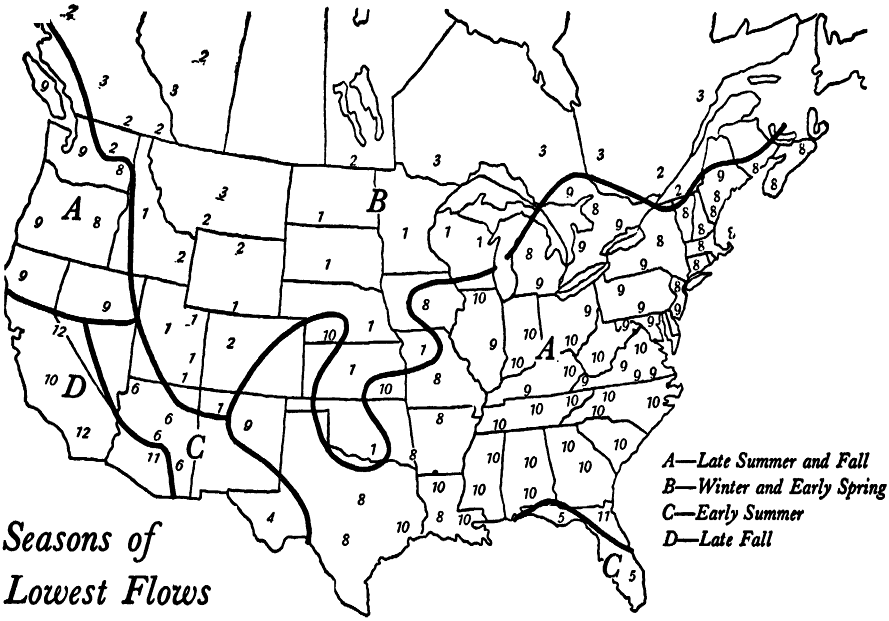
A different effect occurs in the mountain streams in southern California. Drainage basins that are classified on geological evidence as most absorptive and retentive produce the lowest annual runoff for a given depth of annual rainfall, and vice versa. Apparently basins that are low in absorptive qualities shed rainfall rapidly and store little moisture in the soil for subsequent transpiration. On the other hand, high absorptive qualities, where they occur with high soil-moisture capacity, make a relatively large supply of moisture available for transpiration, and so act to reduce runoff.

The second major effect of geology on runoff arises because of a disparity in some places between topographic and phreatic (ground-water) divides.

Runoff is ordinarily computed in terms of inches of depth, based on the surface area enclosed by the topographic divide. Sinks and springs in limestone and lava-rock terranes, however, may so modify the drainage system that the flow in the smaller drainage courses may bear little relationship to the local topography. The movement of ground water in permeable lava rock may be controlled by the buried prelava divides rather than by the present surface. Piracy of ground water may also occur in limestone terrane, where a solution channel may tap water that originates in another surface drainage basin. Water thus pirated appears in the flow of larger, deeply incised streams, or as springs.

In a regional sense, therefore, the limestone or lava does not necessarily affect the total volume of runoff but only its distribution as between one drainage course and another. Outstanding examples of the effect of limestone terrane on the occurrence of the runoff are to be found in Comal County, Tex., in Missouri, and in other places.

The east-flowing streams in the Black Hills region of South Dakota lose a large volume of water in passing through the steep gorges leading from



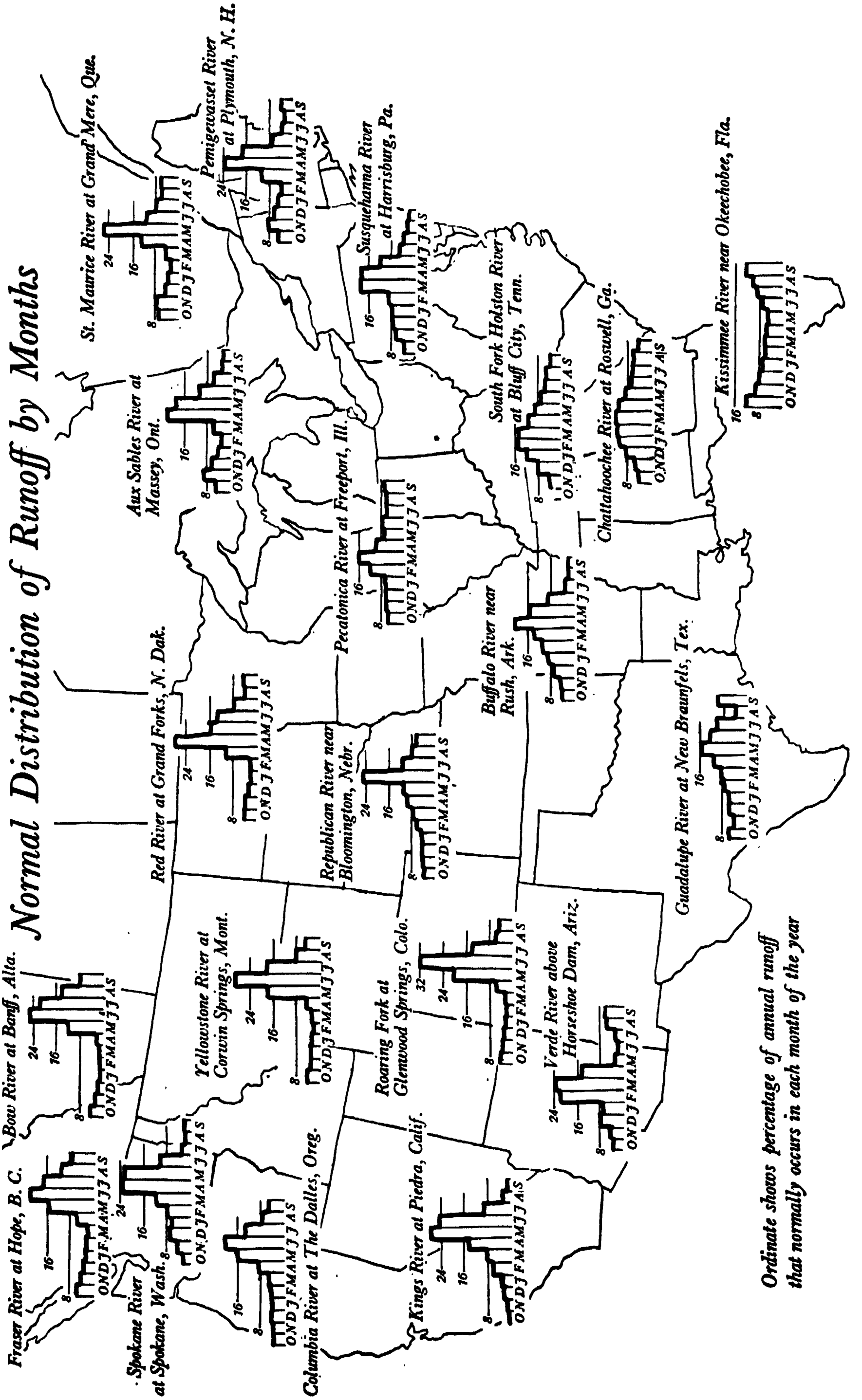
the intermontane valleys to the Great Plains beyond. The water disappears into caves and sinkholes in the massive upturned limestone beds that border the crystalline rocks of the Black Hills and that are crossed by outflowing streams. The water thus recharged to the limestone discharges down the dip, but not necessarily in the same basin.

An example of the effect of topography and geology on runoff in an arid region is found in the part of the High Plains south of the North Platte River, centering roughly about longitude 102° W., and stretching southward almost to the Pecos River. The runoff there is very low, even less than 0.25 inch annually, in a region where the climate would indicate a runoff of nearly 1 inch. The High Plains are remnants of a great fluviatile plain of Tertiary age that once stretched from the Rocky Mountains on the west to the Central Lowland. A feature of the relief on the High Plains is saucerlike depressions ranging in diameter from a few rods to a mile and in depth from a few inches to 30 or 40 feet. After rains, water collects in these basins and is dissipated by evaporation or percolates downward to the water table. A few of the deeper basins contain varying amounts of water perennially.

In the upper Brazos and Colorado River Basins in Texas and New Mexico, nearly 21,000 square miles of the High Plains is considered noncontributing as far as surface outflow is concerned. Because of the flatness and lack of a surface drainage pattern, the High Plains give a nearly perfect opportunity for almost total disposal of precipitation by evapotranspiration. Annual runoff and recharge of ground water average only a fraction of an inch each. The ground water is discharged through seeps and springs at the edges of the High Plains.

The volcanic terranes are like great sponges, and their capacity to absorb runoff is phenomenal. Hundreds of square miles of the lava plains of Idaho, Oregon, California, and New Mexico have no runoff. In some places runoff is lacking even though rainfall may reach 100 inches annually or 10 inches in a single day. The flow of the streams from the mountains that bor-

Normal Distribution of Runoff by Months



Ordinate shows percentage of annual runoff that normally occurs in each month of the year

der such lava plains is also absorbed, and they are therefore often called lost rivers. The water that percolates into the lava reappears in the spring-fed flow of the streams, where they have cut below the water table. Rivers that drain extensive lava beds are generally characterized by their stability of flow. For example, the flow of Deschutes River in Oregon, which drains large volcanic areas, is more stable than any other stream of its size in the United States.

Many of the streams in the desert country are of the quick, flash-flood type, their flow consisting almost entirely of storm water. Some reach to the higher snowfields, and the melt water produces a more sustained flow.

In general, the flow of the mountain streams, although perennial in their headwater and the middle courses, decreases downstream as it traverses the zones of increasing aridity. Upon debouching from the mountains, much of the flow is absorbed by the valley fill, and the streams become intermittent. Farther out on the valley, they disappear entirely.

Seasonal variations between high and low flows in the United States and Canada are shown on the accompanying maps, which are based largely on monthly normals at representative gaging stations. The numbers on the maps designate the calendar months (ranging from January as "1" to December as "12") of highest and lowest normal flow, respectively.

High flows occur from winter to summer, depending upon the region. In southern low-altitude regions, spring is the season of high soil moisture and favorable conditions for runoff from rainfall. But the time of seasonal high water in streams draining northern and high mountain areas is primarily associated with the melting of the accumulated snow, which reaches its climax with the onset of the warm season.

Although snowmelt peaks in Arizona and New Mexico occur in April and May, in the northern parts of British Columbia, Alberta, and Saskatchewan, the late snowmelt delays the seasonal peaks until July.

Superposed on the general south-to-north graduations are the local variations in seasonal high water caused by large differences in altitude, as in the West. The valley tributaries of many streams may reach their seasonal high stages some months earlier than high altitude, snow-fed tributaries.

The Sacramento River Basin in California is typical. High water usually occurs in the lower part of that basin, including the many western tributaries draining the comparatively low Coast Ranges, in February, whereas the headwater tributaries draining the Sierra Nevada do not reach their crests until May or June. Midwinter high flows along the Pacific coast are the result of high rainfall of that season with but little accumulation of snow. Low-altitude dry washes in the southern intermountain region commonly flow only during sporadic storms in summer.

The south-to-north progression of high flow may also be noted in the East, where high flows normally occur in January, February, and March in the Gulf States, and in April and May in Quebec.

The Florida Peninsula, where October is the month of high streamflow, is a noteworthy exception. The rainy season in Florida extends from June to October and streams reach seasonal high stages during the late summer and early fall.

Autumn and winter are generally seasons of low flows. In the East and along the west coast, streams reach their lowest stages in the late summer and fall (after the conclusion of summer's intensive drafts). In the Northeastern States, winter is also a season of low flow, but the intermittent thaws maintain streamflow at rates generally above those of late summer and fall. Farther north, however, as in Quebec, the lowest flows of the year occur in winter, because thaws are infrequent.

Streamflow is seasonally lowest in winter in the Great Plains because of low rainfall. In that season it is also lowest in the intermountain region and

in Canada, generally because of the accumulation of nearly all precipitation in the form of snow that is retained until released during the spring and summer thaws with variations according to latitude and altitude. The low flows in Arizona in June and November coincide with dry months there.

The accompanying map shows the normal distribution of runoff by months at selected gaging stations in the United States and Canada. A marked feature of the chart is that flow is generally greater than the mean annual flow (represented by the 8-percent line shown in full on the graphs) in spring and summer, and that high flows usually prevail for fewer months than low flows. The most marked seasonal concentration is noted in Roaring Fork in Colorado and the central Rocky Mountain region generally, where as much as 30 percent of the annual runoff occurs in June. The least seasonal variation occurs in the Southeast, as illustrated by the graphs for the Chattahoochee and Kissimmee Rivers.

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Underground Sources of Our Water

Harold E. Thomas

The underground reservoirs of water contain the largest storage of fresh water in the Nation—far more than the capacity of all surface reservoirs and lakes, including the Great Lakes.

A. M. Piper, in his report on subsurface facilities of water management and patterns of supply, estimated that the total usable ground water in storage is of the order of 10 years' annual precipitation or 35 years' runoff.

Public interest in ground water has increased greatly in recent years because of the rapidly increasing development and use of wells in many regions and the problems that have accompanied that development. The average citizen knows very little about ground water, and even the hydrologist has less quantitative information than is available on other phases of the hydrologic cycle; this lack has been responsible for many controversies and difficulties in development of water resources.

Of the several phases of the hydrologic cycle, ground water thus is first in usable storage and is also of major interest, concern, and controversy among water users.

Aggregate withdrawals of ground water in 1950 averaged 30 billion to 35 billion gallons a day, or 17 to 20 percent of the total withdrawal for municipal, rural, industrial, and irrigation use. Ground water is unimportant as a direct source for nonwithdrawal uses (hydroelectric power, navigation, waste disposal, recreation, and conservation of fish and wildlife), but it has considerable importance indirectly because the minimum flow of streams is sustained primarily by ground water. Also, the depletion of the ground water in some places has resulted in depletion of streamflow and thereby reduced the supply available for the nonwithdrawal uses.

The rural use of water, not including irrigation, is estimated to be about 3.5 billion gallons a day, of which perhaps 80 percent comes from wells. Wells are widely distributed over the rural areas in nearly all the States, and they provide the bulk of the domestic and the stock-water requirements of farmers.

Municipalities obtain about 3.5 billion gallons a day, or 25 percent of their total withdrawal, from wells and springs. Generally the smaller cities and towns depend on ground water for their supply. Of the 100 largest cities in the United States, only 19 depend on wells for their public supply; 16 of them are among the 60 cities that range in population from 105,000 to 250,000. Of the 22 cities that had 250,000 to 500,000 inhabitants in 1950, only San Antonio and Memphis obtained their municipal supplies from ground water. Houston, Tex., was the only one of the 18 cities of more than 500,000 that depended on wells for all its public supplies, and it has looked increasingly to surface water for industrial use.

The withdrawals by industry of ground water amount to 5.5 billion gallons a day, or about 7 percent of the total requirements of industry. Only 4 percent of industry's requirements in the industrial Northeast comes from wells, but in the western half of the country, where population, industry, and water are all less abundant, industries use almost as much ground water as surface water.

Wells yield about 20 billion gallons a day, or 25 percent of the total withdrawal, for irrigation. California, Arizona, Texas, and New Mexico pump 14 billion gallons a day for irrigation. Irrigation accounts for more than 60 percent of all ground water used in the United States.

THE PUBLIC INTEREST in ground water is paralleled by the interest in stream regulation and development, in weather modification, and in conversion of salt water. This interest stems from the national trend toward the increasing use of water for all purposes, a trend suggesting that in 25 years we shall be wanting twice as much water for industry, irrigation, and municipal use as the 175 billion to 200 billion gallons a day now used.

The selection of ground water as a supply, rather than the surface-water sources, has generally been on the basis of one or more of the following advantages:

1. Ground water may be reached within a few hundred feet of the place where it is to be used, and on the same property, whereas surface water may require pipelines and rights-of-way over stretches of several miles.

2. Ground water may be available for use in areas where the water in streams and lakes has already been appropriated by other users.

3. Yield from wells and springs generally fluctuates less than streamflow in alternating wet and dry periods.

4. Ground water is more uniform in temperature and soluble mineral load than surface water, and is generally free of turbidity and bacterial pollution.

The development of water from surface sources has been a necessity in

many places where ground water can be obtained only at excessive depth below the surface or where it cannot be obtained in sufficient quantity at any depth, where the ground water is deemed to be fully appropriated, or where it is of a quality that makes it unsuitable for the use intended. Even where good-quality ground water is available it may be at a disadvantage as an alternate to surface water in that its use generally requires expenditure of energy for pumping, whereas the surface water may produce energy besides supplying water for other uses.

THE CONTROVERSIAL FEATURES of ground water are numerous. Many disputes as to the effect of one well on another or on a spring have been decided in the courts. Many others undoubtedly have avoided the courts only because of the high cost and the apparent hopelessness of obtaining proof in support of individual opinions. Many of the controversies reflect the general lack of understanding and uncertainty in the public mind regarding ground water.

Ground-water hydrologists will admit—at least to each other—that they can see no farther underground than other people. But by scientific methods they can gain an understanding of the underground conditions that may seem supernatural to a casual observer.

They have learned that the puzzling and apparently mysterious complexity of the occurrence of ground water results to a large extent from the complex geologic history of the earth. Studies of regional geology are prerequisite therefore to an understanding of ground water.

Scientists have done a great deal of research to establish and verify the physical principles that govern the movement of water underground. They apply that theoretical knowledge in their analysis and interpretation of data from wells and springs—well logs, the water-level fluctuations, chemical analyses, discharge data, pumping-test data, and so on. A fuller understanding of the water resources of a region can then be gained by analysis of the relation of ground water to the water in other phases of the hydrologic cycle, both under natural conditions and under conditions of development by man.

Some arguments arise from the conflict between the complexities of the occurrence of ground water in specific areas, as found by hydrologists, and the easy generalizations made by some others concerning ground water throughout a State, or river basin, or the entire country. Some insist, for example, that if we will hold the raindrop where it falls, we will thereby increase the recharge to the Nation's "ground-water reservoir." Obviously, if the earth's crust were homogeneous enough and permeable enough to accept the rain that falls at any point, there would be no uncertainties in the development of wells, and wells of large yield could be drilled anywhere.

I think controversies about ground water are a good omen. Although they stem from incomplete knowledge of the resource, they show that we now have a little knowledge of it. And that is better for the Nation's economy than our past failures to give any thought to ground-water aspects of water-development projects. We need to know much more, and we need especially the detailed knowledge of specific localities. The variations in the rock materials that hold and yield water are such that it is hazardous to bypass the necessary specific studies of ground water, even though they take time and money.

THE WATER BENEATH the land surface is not all ground water. A man with his feet on the ground might assume that by picking up a handful of moist earth he obtains some ground water, or that in pouring a bucketful of water upon absorbent land he increases the ground-water resources by that amount. Those assumptions are incorrect.

Ground water is only the part of the

subterranean water that occurs where all pores in the containing rock materials are saturated. The "zone of saturation" may extend up to the land surface in some places, notably in seep areas and in some stream channels, lakes, and marshes. At all other places, above the ground-water zone, "a zone of aeration" exists that may range in thickness from a few inches to hundreds of feet. Some water is in the zone of aeration at all times, held there by molecular attraction—in particular, soils may hold significant volumes of water against the downward pull of gravity. Wells cannot extract any of this water; they must be drilled through the zone of aeration and obtain their supplies from ground water.

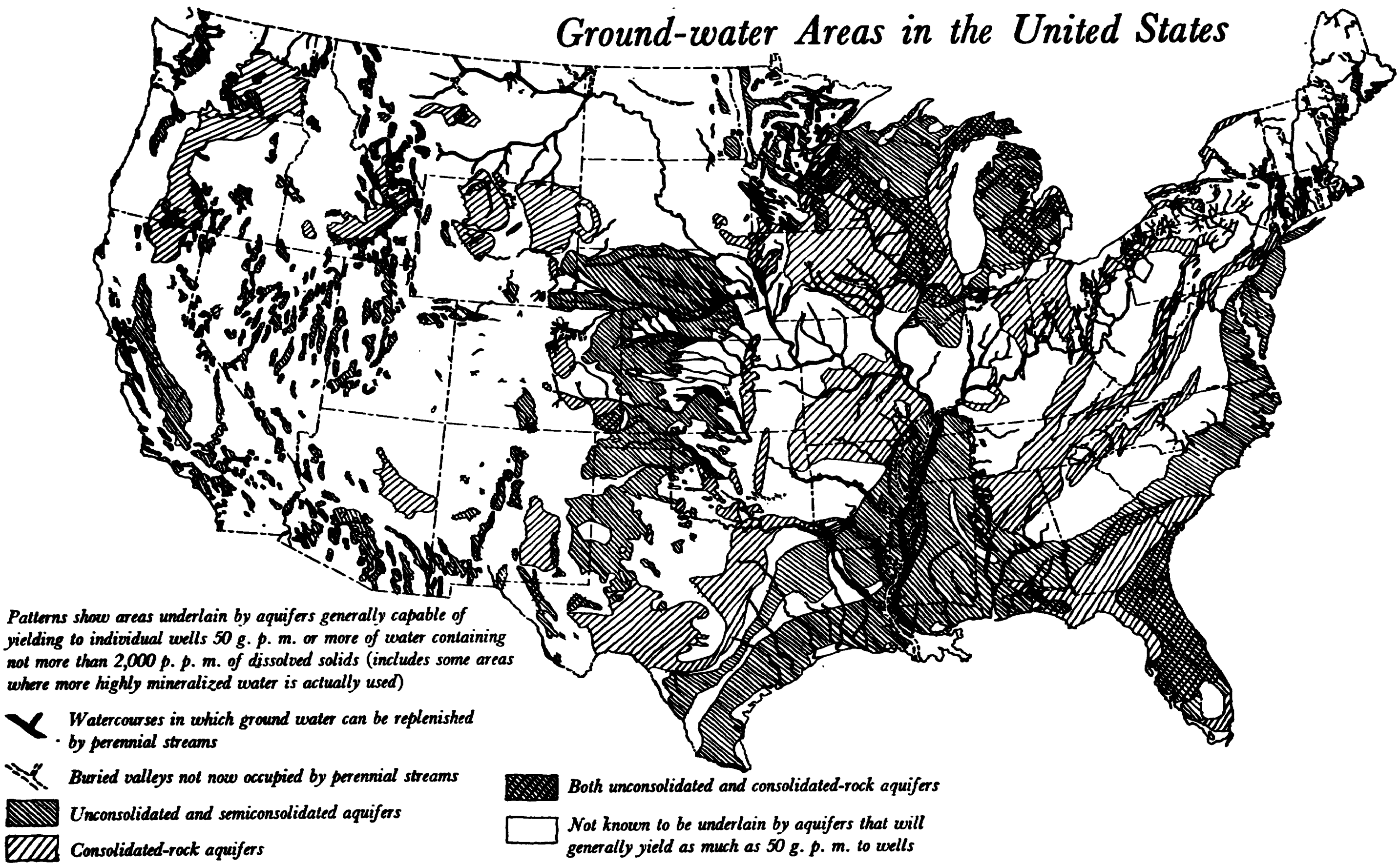
The normal field of operations of the ground-water hydrologist is delimited only approximately by such a definition of ground water. Thus the top of the zone of saturation cannot readily be identified from the land surface. The hydrologist therefore measures the water levels in shallow wells. From the measurements he constructs a map of the "water table," which is thus a phreatic surface—that is, pertaining to a well—where the water is at atmospheric pressure. The water table may coincide approximately with the top of the zone of saturation in coarse gravel but is likely to be several inches or even several feet below it in finer grained materials, because capillary rise results in the saturation of a zone above the water table (the capillary fringe).

Often it is hard to identify or classify subterranean water on the basis of the definition above. There may be saturated flow, at least temporarily, in parts of the soil zone. A well driller may encounter a saturated zone and then continue on down into dry materials, obviously in the zone of aeration. Or he may find saturated materials that yield no water to his well, so that there is no water table. And he may drill through materials that yield no water, and then encounter a stratum from which water rises in the well to a level high in the zone of aeration, and the water may even overflow. All these are typical of the wide range in conditions of occurrence of ground water. They reflect the great variations in porosity and permeability of the solid components of the earth's crust.

All subterranean water occurs in open spaces within the rock materials of the earth's crust. There are many kinds of rocks, and in the number, size, and shape of their open spaces they differ greatly. Loose materials like sand, gravel, and rock fragments have pore spaces that are easily seen, but the spaces between particles of clay and other fine-textured materials may be exceedingly minute. Of the so-called solid rocks, some contain microscopic pores; others have large caverns; still others are exceedingly dense and compact—but even they are commonly fractured enough to form some openings that can admit water. All openings underground may be regarded as pores, for even the largest cavern is no more than a pore in comparison to the size of the earth. The ability of rock material to hold and yield water is determined largely by the characteristics of those pores.

The porosity of loose rock materials varies with the arrangement, shape, and degree of assortment of the particles. The size of grain is not a determining factor, because, if other conditions are the same, a material will have the same porosity whether it consists of large or small grains. Silt or clay, consisting entirely of minute particles, may have a porosity as great as coarse gravel, although the pores are less easily seen. In some consolidated rocks the original porosity has been reduced by compaction or by deposition of cement in the pore spaces. In others it has been increased by development of fractures or by the dissolving of some of the rock material.

Rocks of low porosity are necessarily limited in their capacity to absorb, hold, or yield water. Such rocks may


Ground-water Areas in the United States
Patterns show areas underlain by aquifers generally capable of yielding to individual wells 50 g. p. m. or more of water containing not more than 2,000 p. p. m. of dissolved solids (includes some areas where more highly mineralized water is actually used)
Watercourses in which ground water can be replenished by perennial streams
Buried valleys not now occupied by perennial streams
Unconsolidated and semiconsolidated aquifers
Consolidated-rock aquifers
Both unconsolidated and consolidated-rock aquifers
Not known to be underlain by aquifers that will generally yield as much as 50 g. p. m. to wells

occur very close to the earth's surface, although, on the average, the porosity tends to be higher near the surface and lower with increasing depth. The least porous rocks are probably those that are buried so deeply that the weight upon them is enough to distort the rock structure and close all pores—a depth that is obviously greater for strong rocks than for weak rocks.

The depth at which pressures are great enough to force closure of pores in all rocks—that is, the depth to the zone of the rock flowage—must be greater than the 4 miles that has been penetrated in the deepest test wells for oil, and is believed to be 10 miles or more. The top of the zone of rock flowage is the theoretical lower limit to which ground water will penetrate.

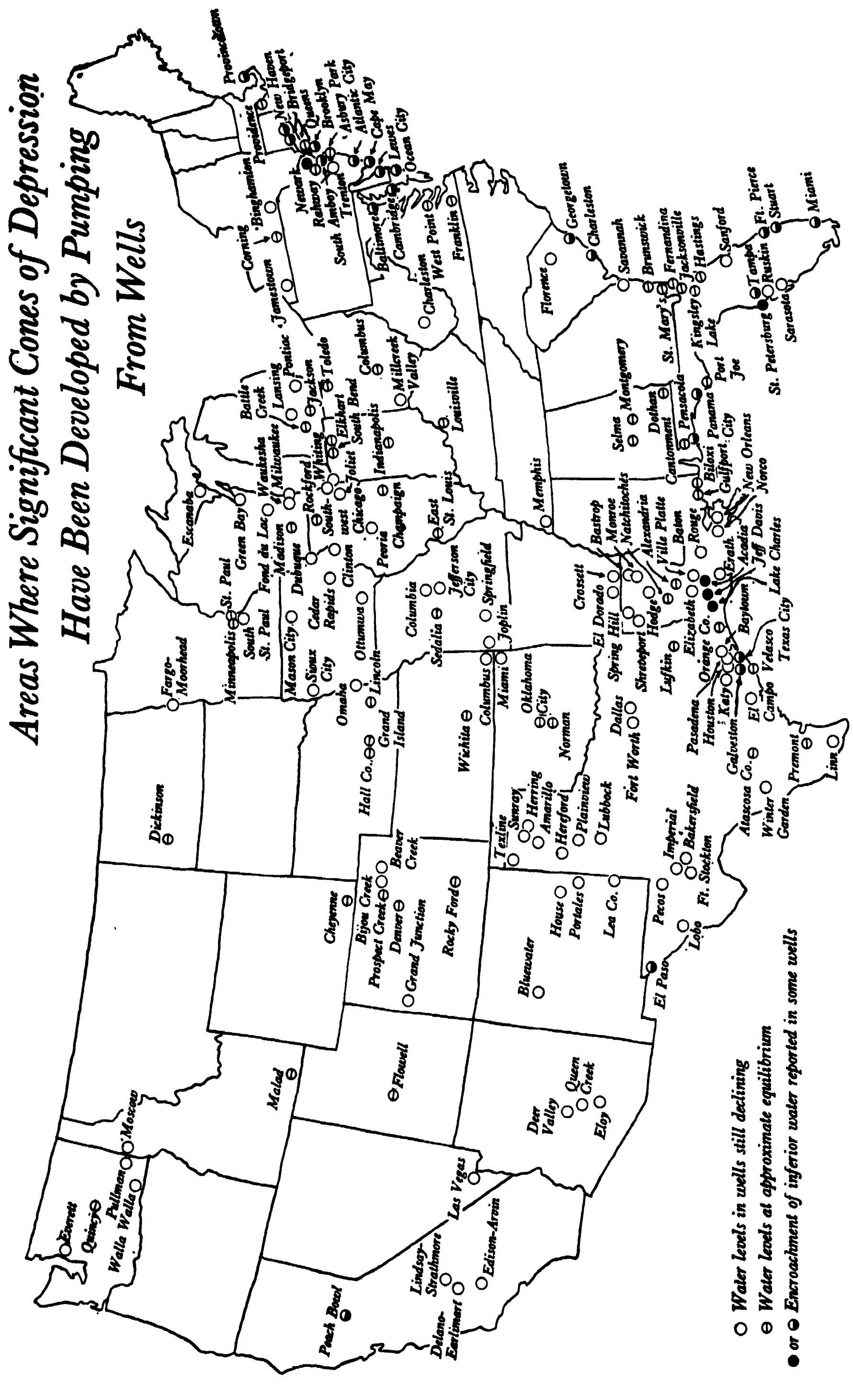
Evidence from deep wells indicates that in most places water becomes scarce far above that theoretical depth. A few wells have obtained water from rocks at depths of more than 2 miles, but in most places deep wells find little water below a depth of half a mile.

Rock materials of high porosity can yield copious quantities of water, but not necessarily. One saturated rock may yield most of the water in its pores to wells or springs. Another, of equal porosity but smaller pores, may retain practically all its water and yield negligible amounts to wells. The difference then is in the proportion of the contained water that is held by molecular attraction and the proportion that can be moved by gravity. The rock that permits water to move through it by gravity is far more permeable than the one that holds water by molecular attraction.

Molecular attraction becomes more and more significant with declining size of pore because of the larger surface area of solid material to which water can adhere. In a cubic foot of well sorted gravel whose particles are a quarter of an inch in diameter, the combined surface area of the grains is about 200 square feet, or about the floor space of an average living room. In a well sorted sediment of rounded, clay-size grains 0.001 millimeter in diameter, the porosity may be equal to that of the gravel, but the surface area of the grains in a cubic foot may exceed a million square feet, or about 23 acres, and the molecular attraction for water is correspondingly greater.

Within the earth's crust is one zone of generally high porosity and water-retaining ability that is of prime interest to agriculture—the soil zone. Although that zone is similar in many respects to the underlying material, and indeed inherits many of the characteristics of the rock material from which it was formed, it has several important differences. Situated where it is, and acting as it does as a support and food-and-moisture medium for plant growth, it tends to accumulate organic matter and may become more proficient than its parent material, both in the amount of water it can hold against the pull of gravity and in the amount it can transmit without damage to itself when precipitation exceeds its moisture requirements. But the soil is particularly susceptible to changes in its water-retaining and water-transmitting properties as the result of the activities of man. Thus it is the differences between soil and the underlying rocks—rather than the similarities—that are important in considering the relation of soil to water supply. The soil does not yield water to wells, but through it must move a large part of the water that does become available for man's use later. The underlying rocks do yield water to wells, but they do so only if the soil or other surficial material, which has first call on the water, is able to release a part of it for downward movement to the water table.

Below the depths that can be reached by plant roots, the water dominated by molecular forces cannot be of major economic importance, because it is not yielded readily to wells or to springs where mankind can put it to use. The force of gravity continues to operate even upon the waters in those minute pores, however, so that small amounts of water may be yielded to wells in


Areas Where Significant Cones of Depression Have Been Developed by Pumping From Wells
○ Water levels in wells still declining
⊖ Water levels at approximate equilibrium
● or ◐ Encroachment of inferior water reported in some wells
Everett
Quincy
Pullman
Walla Walla
Moscow
Malad
Dickinson
Cheyenne
Flowell
Peach Bowl
Delano-Earlimart
Lindsay-Strathmore
Edison-Arvin
Las Vegas
Deer Valley
Queen Creek
Eloy
Bluewater
Bijou Creek
Prospect Creek
Denver
Grand Junction
Beaver Creek
Rocky Ford
House
Portales
Lea Co.
Pecos
Lobo
El Paso
Texline
Sunray
Herring
Amarillo
Hereford
Plainview
Lubbock
Imperial
Bakersfield
Ft. Stockton
Hall Co.
Grand Island
Wichita
Norman
Oklahoma City
Fort Worth
Dallas
Atascosa Co.
Winter Garden
Premont
Linn
Galveston Co.
El Campo
Pasadena
Houston
Katy
Galveston
Fargo-Moorhead
Minneapolis
South St. Paul
St. Paul
Mason City
Sioux City
Omaha
Lincoln
Ottumwa
Columbus
Miami
Joplin
Sedalia
Columbia
Jefferson City
Springfield
Escanaba
Green Bay
Fond du Lac
Madison
Dubuque
Cedar Rapids
Clinton
Rockford
Milwaukee
Waukesha
South-west Chicago
Peoria
Champaign
East St. Louis
Joliet
Whiting
Elkhart
South Bend
Indianapolis
Battle Creek
Lansing
Jackson
Pontiac
Toledo
Columbus
Millcreek Valley
Louisville
Memphis
El Dorado
Spring Hill
Crossett
Shreveport
Bastrop
Monroe
Natchitoches
Alexandria
Ville Platte
Hodge
Lufkin
Elizabeth
Orange Co.
Baytown
Velasco
Texas City
Baton Rouge
Erath
Acadia
Jeff Davis
Lake Charles
New Orleans
Norco
Biloxi
Gulfport
Panama City
Pensacola
Cantonment
Dothan
Selma
Montgomery
Port St. Joe
St. Marys
Kingsley Lake
Savannah
Brunswick
Fernandina
Jacksonville
Hastings
Sanford
Tampa
St. Petersburg
Ruskin
Sarasota
Ft. Pierce
Stuart
Miami
Florence
Georgetown
Charleston
Franklin
West Point
Charleston
Baltimore
Cambridge
Lewes
Ocean City
Cape May
Atlantic City
Asbury Park
Trenton
South Amboy
Rahway
Newark
Brooklyn
Queens
Bridgeport
New Haven
Providence
Provincetown
Binghamton
Corning
Jamestown

time. Thus there is slow drainage of water into many wells dug into clay or other fine-textured materials, enough for limited domestic and stock use. In some areas of heavy pumping, the drainage from saturated clays has been accompanied by compaction and has caused the land surface to subside.

The rate of movement of water beneath the surface depends a great deal on the permeability of the rock material, which is its capacity for transmitting water. In permeable materials, gravity is the force that moves water downward from the land surface to the zone where all pores are saturated, thence laterally toward lower elevations, and ultimately to the oceans or to places where the water is discharged at the land surface by springs or seeps, or by evaporation or transpiration.

In the development of ground water by means of wells, a hole is drilled into the zone of saturation. Water that drains from the saturated rock materials into the well is called gravity ground water. As that water is pumped out, other water moves toward the well. The rate at which water moves toward the well, and therefore the rate at which water can be withdrawn from the well, depends largely on the permeability of the materials from which the water is drawn.

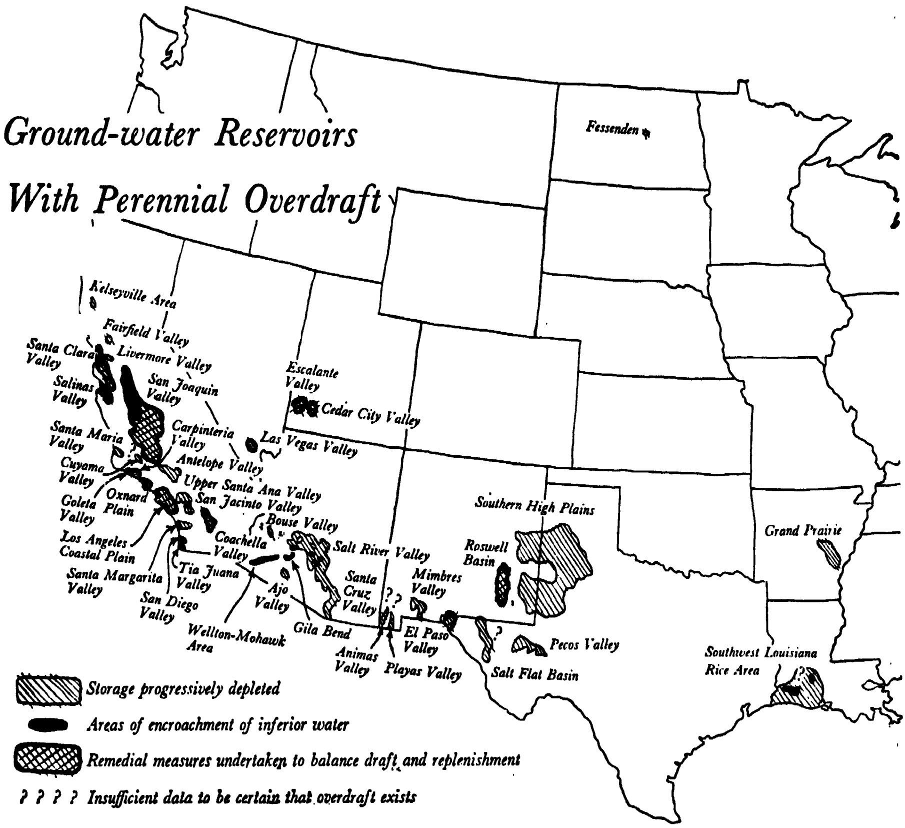
THE SCIENCE OF GEOLOGY deals in part with the stratigraphy and structure of the rock formations that make up the earth's crust. Those geologic formations are the framework through which ground water moves or is barred from movement. A formation that will yield enough water to be important as a source of supply is called an aquifer—a water-bearing formation that contains gravity ground water.

Nature provides a gradation from highly permeable materials which, if saturated, are very productive aquifers, to impermeable materials that yield practically no water. Thus a classification of rock materials merely as permeable or impermeable is in most places an oversimplification of the actual conditions. Indeed, a formation classed as an aquifer in a region nearly destitute of available water might be viewed as unworthy of the name in regions where very large supplies can be obtained from wells tapping other formations. The term "aquifer" is sometimes used to designate individual water-bearing beds, perhaps only a few feet thick, and sometimes to designate thick series of beds of varying permeability, where the individual beds are more or less interconnected hydraulically.

The term "ground-water reservoir" also has rather flexible usage. Commonly it is used interchangeably with aquifer. More broadly it may represent the water-bearing materials in an extensive area, as for example the San Joaquin Valley ground-water reservoir in California, which supplies water equal to about a quarter of all the water pumped from wells in the United States. Still more loosely, the term has been used to designate all the rock material of a continent, but such loose usage ignores the contrasts in permeability and the resulting contrasts in capabilities as to storage and development of ground water.

Great variations in permeability of rock materials have been chiefly responsible for the considerable variation in occurrence of water in the ground-water reservoirs of the continent. In some areas the ground-water reservoir and the materials above it are all relatively permeable, although some variation is almost inevitable. Wells dug or drilled in those areas commonly penetrate first some dry strata, then materials that are increasingly moist (the capillary fringe), and then materials from which water enters the well—thus they have gone through the zone of aeration and reached the zone of saturation. The water table rises as water enters the ground-water reservoir; it falls as water drains away to lower parts of the reservoir or as it is discharged by wells or other means. That water is unconfined.

Relatively impermeable layers with-



in the zone of aeration produce various complications in this simple picture. Such layers may be right at the surface, so that there can be very little infiltration, and practically all the water from precipitation must collect on the surface or run off overland.

IMPERMEABLE MATERIAL may be present at various depths below the land surface, whether as hardpan within the soil zone, or clay or other tight material at greater depth. Such material may be poorly permeable and thus retard downward percolation, so that there is an accumulation of water and temporary saturation of material immediately above it. Or it may be so impermeable as to prevent downward percolation, so that a ground-water reservoir is permanently maintained above the impermeable zone. Such bodies of ground water within the zone of aeration are perched. Many are of very small extent and may disappear in a short time after rains. Some perched ground-water reservoirs yield water to wells and springs and are thus of economic value, but they are of very minor importance in the Nation's overall water economy.

Many deep wells penetrate far into the zone of saturation, and go through rock materials that range widely in their permeability. Water may rise markedly above the top of the aquifer whence it comes, and may even overflow at the surface. Such water is confined beneath less permeable material. It is not necessary that the confining bed be impermeable, but only that it be less permeable than the aquifer. Thus the Dakota sandstone in North Dakota and South Dakota is a famous

artesian aquifer in which water is confined beneath dense shale. At the base of the Wasatch Range in Utah there are beds of loose sand more permeable than the Dakota sandstone; nevertheless, that sand constitutes the confining bed above coarse gravel. In both instances water moves far more easily through the aquifer tapped by wells than through the overlying beds. If the water in the aquifer is under sufficient pressure to rise above the zone of saturation, it is artesian, and the aquifer is then an artesian reservoir.

An artesian reservoir does not receive any water by downward movement through the confining bed that overlies it. Even in places where the confining bed is moderately permeable the artesian pressure opposes such movement. An artesian reservoir as a rule therefore is replenished in some area where the confining bed does not exist and where ground water is under water-table conditions. Thus, although it is important to differentiate between confined and unconfined waters—because of the differences in ground-water hydraulics—it should be recognized that an "artesian reservoir" is actually only a part of the complete underground system necessary for yielding perennial supplies to wells or springs. For artesian aquifers, as well as for other ground-water reservoirs, there must be some area in which the soil or other surficial material and any underlying unsaturated material are sufficiently permeable to permit water to enter the aquifer. Such areas are the recharge areas for ground-water reservoirs—the areas in which replenishment occurs.

CONFINED WATER has also been encountered in wells in many parts of the country, particularly in oilfields, under conditions that indicate that it has been isolated from other waters and (in many instances) that it has been trapped there for geologic ages. The trapped waters generally are highly mineralized and not usable, but some contain minerals of economic value. Trapped waters are found under conditions analogous to those requisite for petroleum accumulation, and they are similar to the petroleum resources in another respect: Being isolated from the natural circulating system of the hydrologic cycle, they are not renewable or replenishable as are most water resources.

THE AMOUNT OF STORAGE in a ground-water reservoir is no indication of the capabilities of the reservoir for sustained yield of water to the wells and springs. The limit of perennial yield is set by the average annual recharge to the reservoir, just as the useful yield of a surface reservoir is set by the inflow to it. Some small ground-water reservoirs along streams are capable of a large sustained yield because they are readily recharged from the stream. Others, notably in desert areas, may be far larger and hold vast quantities of water in storage, but yet have very low capabilities for perennial yield because of meager recharge. As an example, the ground-water reservoir under a 6,700-square-mile area in the Southern High Plains of Texas is estimated to hold more than 5 times as much water as Lake Mead (formed by Hoover Dam), but its annual recharge is less than 0.5 percent of the annual inflow to Lake Mead.

Characteristically there is natural movement of water through ground-water reservoirs, but that movement is at snail's pace. Whereas stream velocities are commonly quoted in terms of feet per second, ground-water velocities are measured in feet per day or even feet per year. The ground water moves from recharge areas to areas of natural discharge, and through the years the average natural discharge from the reservoir is equivalent to the average recharge. Wells intercept some of the water along its route, and if their yield is sustained year after year, it is because the water drawn by them is replaced by increased recharge, or is diverted from its course toward ultimate natural discharge.

As a rule, water will not remain un-

der a piece of property until the owner is ready to use it: Eventually it will be discharged from the ground-water reservoir whether he takes it out or not. In other words, conservation of ground water is not necessarily achieved by not using it.

The velocity of ground-water movement is an important factor determining the sustained yield of wells, for that yield is limited to the quantity of water that moves to the well from the places where the water entered the ground. Wells remote from a source of replenishment cannot yield water perennially at rates greater than the rate at which water moves through the aquifer, even though the quantity available at the source is many times as great.

Artesian supplies in particular are limited by this factor of transmissivity of the aquifer, and many of the Nation's problems of "failing water supplies" stem from this limitation. The problems are analogous to those of a town that has an adequate overall water supply but has distribution lines too small to carry the water needed in some parts of the town.

Some guides may be offered for the effective development of underground storage for perennial use. The sustained yield of a ground-water reservoir (using the term to describe an underground unit of the hydrologic cycle, with its areas of recharge and discharge) cannot be greater than the average recharge, whether that recharge occurs by natural or artificial means, or both. Generally the quantity recovered from the entire reservoir for use will be appreciably less than that inflow, because of the practical limitations of the recovery techniques. In any part of the reservoir—even at any particular well—a further limitation is imposed by the rate at which water can be transmitted through the aquifer. This limitation applies least to wells within the recharge area, where they can reap the benefit of any inflow in short order. The limitations are an oversimplification of a complex problem and are only the hydrologic limitations. In many regions economic, social, or legal factors limit the yield of ground-water reservoirs to a rate far below their hydrologic capabilities.

The relation between recharge and sustained yield of ground-water reservoirs is so closely analogous to that between inflow and yield of surface reservoirs that one might wonder why ground-water development programs are not based on a knowledge of the recharge comparable to the knowledge of streamflow that we consider to be prerequisite to development of rivers. Part of the answer may lie in the fact that the developed surface storage is a product of man's ingenuity and does not exist until he has made a substantial investment in labor and materials; whereas the ground-water reservoir is developed and filled by Nature and lies ready to yield water for a small investment in well drilling. At any rate, "ground-water shortages" have been reported in areas in nearly every State, and most of the difficulties could have been mitigated if the hydrology of the ground-water reservoirs had been known.

In extensive areas the surficial materials are permeable but unsaturated. In some places such materials may extend to depths of several hundred feet. They do not come within the definition of "aquifers" or "ground-water reservoirs," which are limited to saturated rocks. But they can be classed as potential underground-reservoir sites, which may be placed in service if suitable methods can be found for saturating them. Indeed, there are already ground-water reservoirs in the irrigated areas of the West that once were composed of unsaturated rocks but that now receive the excess water from irrigation, store it, and subsequently release it to wells and springs. There also are unsaturated rocks that will probably never provide satisfactory reservoirs, even though they are exceedingly permeable, because the materials are in places where water would drain out as fast as it could be added practically.

THE GROUND-WATER PHASE of the hydrologic cycle may now be described with reference to the framework of rock materials that hold or transmit subterranean water. Practically all ground water, like soil moisture, is derived ultimately from precipitation. There are other sources of ground water: Juvenile water rising from the earth's interior, as in some volcanic areas; connate water trapped in sediments at the time of their deposition perhaps hundreds of millions of years ago; water contained in certain minerals and released when those minerals decompose. The quantity from those sources may be large in the aggregate, but the water is commonly too mineralized for most uses and is therefore avoided when encountered in wells. Essentially all usable ground water is part of the circulatory pattern of the hydrologic cycle.

Permeability is a major factor in all aspects of subterranean water movement. It is important at the land surface in determining the proportions of infiltration and overland flow from precipitation. This proportion may be modified by climatic factors, and the permeability also may be modified by various factors. Variations in permeability below the surface are responsible for perched ground-water zones and for artesian conditions, as well as for the marked contrasts in yield of water-bearing formations and for the failure of some rock materials to yield water.

Probably no part of the earth's crust is absolutely impermeable. It follows that in most places some water may move down from the land surface and that there should be at least small amounts of ground water under practically every point of the land surface. The wide distribution of wells at farmhouses and populated places supports this contention. But the specifications set by mankind for water supply from a well are such as to disqualify many regions. Most clays and fine-textured materials are scorned because a well cannot pull out the water stored in them. The needs of some users are so great that they cannot be met even from moderately permeable material. Many aquifers are not used because their water fails to meet desired standards as to chemical quality. And others may be so deep that drilling wells or pumping water from them cannot be justified economically.

Particularly for the large wells required for industry, irrigation, and municipal use, only the best aquifers suffice. It is estimated that nearly 80 percent of all water obtained from wells comes from loose or only slightly consolidated gravel and sand. Limestone yields about 5 percent of the total water pumped from wells, chiefly in Florida, Georgia, New Mexico, and Texas. About 3 percent comes from sandstone in various parts of the country, and 2 percent from basalt, chiefly in the Pacific Northwest.

An accompanying map (page 66) shows the areas in which moderate to large supplies of usable water may be obtained from wells. The depth of the aquifer below the land surface was not taken as an essential criterion in the compilation of the map. In some areas the depth may be too great for drilling under present economic conditions, but the water remains available whenever it is needed. In some areas, furthermore, water may be encountered at several depths, perhaps in more than one geologic formation.

Thus the map includes all areas in which moderate to large quantities of usable water can pass through permeable materials. The scale of the map and the extent of knowledge are too small to show this information in great detail. Successful large wells have been drilled in many small areas that could not be shown, and on the other hand satisfactory wells cannot be obtained at every single place within the outlined "ground-water areas."

Three types of ground-water areas are distinguished on the map:

1. Watercourses, consisting of a channel occupied by a perennial stream, together with the enclosing and underlying alluvial material satu-

rated with water that comes from the stream, from infiltration at the surface, or from adjacent water-bearing materials.

2. Loose water-bearing materials, chiefly gravel and sand, including the productive aquifers of the Coastal Plains, Great Plains, glacial drift and outwash, and western valleys. Buried glacial valleys not now occupied by perennial streams are included in this group. The areas shown include known and potential areas of well development as well as the recharge areas.

3. Consolidated water-bearing rocks, of which limestone, basalt, and sandstone are the most important. The areas include the recharge localities, which generally coincide with the areas of outcroping of the permeable rocks, as well as areas where the rocks are buried beneath less permeable materials but yield usable water to wells.

The blank areas of the map are significant because they indicate that about half of the country is not known to be underlain at any depth by rock materials that can yield as much as 50 g. p. m. (gallons per minute) to a well. Apparently the rocks underlying these blank areas are generally incapable of receiving or transmitting large quantities of water, either by infiltration from the land surface or from streams or by underflow from adjacent areas underlain by permeable rocks. These areas of course are not devoid of ground water, and many will yield adequate supplies for domestic or stock use. Because of the overall low permeability of the rocks or overlying mantle in these localities, the ground-water phase of the hydrologic cycle carries a smaller than average proportion of the total water, and, on the average, probably for shorter distances.

Recharge to practically all ground-water reservoirs—whether large or small, important or negligible—moves downward from the surface. The amount of recharge depends partly on the permeability of the soil or mantle rock and partly on the available water from precipitation or streams or other sources. Many of the best recharge areas are underlain by materials so permeable that they would not be classed as soils at all, because water moves down through them so rapidly that they support little vegetation: The talus on mountain slopes, the bouldery beds of streams at the mouths of canyons, barren lavas, sand dunes, and areas of outcrop of cavernous limestone.

In most ground-water reservoirs only a part—and perhaps a very small part—of the infiltration in the recharge area becomes ground water. Near the land surface water may be pulled upward by solar energy—evaporation or transpiration—and returned to the atmosphere. In desert basins most of the water from the scant precipitation is dissipated in this way, and the ground-water reservoirs may be recharged only a few times a century, during exceptional "wet" years.

Even in the humid eastern half of the country, many ground-water reservoirs receive negligible recharge during the summer, suggesting that vegetation may consume most, if not all, of the water made available to it by rains during the growing season.

The water that descends below the root zone is beyond the influence of the sun's energy, and its movements thereafter are impelled by gravity alone. It obviously moves in response to gravity as it goes down to the zone of saturation, but it no less truly moves in response to gravity as it rises in spring orifices or flowing wells or seeps upward through so-called confining layers. Most of the movement in the ground-water phase is lateral—down gradient—rather than in a vertical plane. In this respect it is similar to movement in the surface-water phase.

BASIC DATA that are essential for an understanding of our ground-water resources (and similarly for surface-water resources) have been collected by numerous Federal, State, and municipal agencies, by irrigation districts and

other groups of water users, industrial firms, consulting specialists on water, and individuals who have become interested in some aspects of water supply.

Some examples: Well drillers develop a fund of valuable information concerning the position and characteristics of aquifers in a region and how to develop water from them. On the basis of their information, many drilling companies can contract to drill wells of guaranteed yield and quality. Pump manufacturers and power companies may rate the discharge and efficiency of installed pumping equipment. Municipalities and many industries have a permanent staff of water-supply specialists; some of them are concerned mostly with distribution and treatment, but some keep records of quantities pumped from wells and of fluctuations of static level and pumping lift. Irrigation districts and reclamation projects in the West may have data on water levels in wells, particularly if some of their supply is from ground water or if they are troubled by a high water table. Technical advisers to many soil conservation districts accumulate considerable data on various aspects of ground water within the district. County agents, State agricultural colleges, and others related directly or indirectly to the Department of Agriculture have also been responsible for collecting various records from wells. Operators of mines, tunnels, oil or brine wells, levee systems, and other flood-protection structures also collect some data concerning special aspects of ground water.

So we have a formidable list of individuals, companies, and governmental agencies who collect ground-water data at specific installations or for specific types of use: The bureaus in the Department of the Interior concerned with reclamation or with administration of Indian lands, national parks, or other public lands; several agencies in the Department of Agriculture; some agencies in the Department of Defense, including the Corps of Engineers; numerous State agencies having responsibilities parallel to the Federal agencies; municipalities and industries; water-users' groups; universities and other scientific or technical groups; and individuals. For a comprehensive evaluation of the ground-water resources and their development, each is likely to have a jigsaw puzzle, most of whose pieces are missing.

I cite several reasons. The data may be collected sporadically, when water-supply difficulties are present or imminent or during the tenure of an employee whose scientific interest impels him to go beyond his routine assignments. The data may be limited as to scope or area, and (although they presumably meet the special needs of the collector) they do not explain the occurrence and movement of the ground water in the region. Finally, the data collected by special-interest groups generally are not available for public use. Some are disseminated among groups who will make it available to all upon request, but some are held by people in regions of keen competition for water supplies, who have collected the data for competitive advantage.

A few agencies have responsibility for collecting data leading to comprehensive evaluation of water resources and the effects of development. In the important field of public health in relation to the water supply, the Public Health Service of the Department of Health, Education, and Welfare maintains standards in close coordination with the responsible State agencies.

The collection and interpretation of basic data pertaining to all aspects of ground-water resources is the responsibility of the Geological Survey of the Department of the Interior, working in coordination with the State agencies responsible for appraisal of water resources and the effects of development. These agencies may receive substantial cooperation and assistance from the numerous special-interest groups who collect water data for their own needs. Also, several States have statutes requiring submission of certain data—such as drillers' logs, data as to depth,

discharge, use of a well, and so on—to the State engineer, State geologist, State land commissioner, or other officials responsible for data on water resources.

Wherever the ground-water development is controlled by statute, the State engineer or other administrator may issue permits or approve applications for new wells or adjudicate water rights in a ground-water basin. He may be designated as referee in cases before the courts and provide the hydrologic basis for a decision. Thus he has quasi-judicial functions, subject to review by the courts. The Geological Survey commonly collects and interprets basic data in cooperation with the State agency. It qualifies for this task on the basis of the competence, impartiality, and freedom from special interest of its ground-water hydrologists.

But all the available ground-water data and the analytical studies give us much less than a complete picture of the resource throughout the country. Americans tend to give attention to the ground-water resources when troubles appear. We know most about the regions where crises have developed, therefore, and far less about other regions. So it might be until the well runs dry; then—to paraphrase Benjamin Franklin—we shall know the worth of water.

The problems of ground-water development have been discussed in some detail in my book, *The Conservation of Ground Water*. A summary of the problems, adapted from that volume, is given:

The ground-water problems of one locality are rarely unique, for other localities have encountered similar problems and in many instances have found satisfactory solutions. Most of the problems of ground-water "shortage" are in areas where significant quantities of water are withdrawn from wells.

Ground-water storage has also been changed by other activities of man, sometimes to his benefit, but more often to his disadvantage. Very commonly the changes, incidental to the settlement of the country, have been unintentional and unforeseen.

The difficulties created by pumping from wells are of several types. Some problems pertain to entire ground-water reservoirs, where the rate of replenishment is inadequate to meet the continuing demand. Pipeline problems (problems arising from inadequate capacity of aquifers to transmit needed quantities of water to points of use) arise because of the inability of water to move rapidly enough through earth materials to supply the demand of wells, even though the ground-water reservoir as a whole may have an adequate supply of water. The third type occurs along watercourses, where an intimate relation exists between the water in the stream and that pumped from wells.

The serious problems of ground-water shortage occur in areas where water is pumped out faster than the entire ground-water reservoir is replenished. Under those conditions the reservoir is being emptied of water that may have taken decades or centuries to accumulate, and there is no possibility of a continuous perennial supply unless present conditions are changed. Even more serious is the condition where salty or otherwise unusable water flows into a ground-water reservoir as the good water is pumped out, for those reservoirs may be ruined before they are emptied. Most of the excessively pumped reservoirs are in the arid regions, where precipitation is generally inadequate for the needs of man. Some have an area of a hundred square miles or less; others may embrace several counties or extend across State or international boundaries. Users of ground water generally are aware that they are using more than the perennial supply and that the supply will be exhausted unless action is taken. Corrective measures already applied in some areas include prevention of waste, a pro rata reduction of pumping from all wells, prohibition of further development, reclaiming of

used water, artificial ground-water replenishment by surplus stream water, and importation of water from other areas.

Pumping from closely spaced wells has caused significant declines of water level in parts of nearly every State, chiefly in municipal or industrial areas that use large quantities of ground water. The water levels have reached approximate equilibrium in some of those areas, indicating that the pumped water is now being replaced by the water transmitted through the aquifer. In other areas the water levels are still declining each year. Concentrated draft has induced an inflow of ocean water or other unusable water to some wells.

The watercourse problems result from the pumping wells along rivers, where the ground water is so closely related to the water in the stream that pumping from wells depletes the streamflow. Diversions from the stream for various purposes may increase the amount of ground water at one place and reduce it at another. The intimate relation between surface and ground water is also shown at some river cities where protection from floods requires not only protection from a rise in the river but also protection from the simultaneous rise of ground-water levels under the city.

Many activities unrelated to pumping of ground water have modified the storage of water below the land surface. Drainage projects and irrigation projects have proved that it is possible to manipulate the storage in ground-water reservoirs. Unfortunately ground-water storage has been increased by irrigation in some places until good agricultural lands have been waterlogged and abandoned; and it has been decreased in other localities by drainage to the detriment of agricultural use of the land or municipal use of the water. Man has changed the quantity of water stored underground by his structures for storage of surface water or for protection against floods, by improving the channels for navigation, and by building cities and providing them with storm sewers. He has damaged some water supplies by discharging contaminated water into the ground or into streams from which it enters ground-water reservoirs, and also by puncturing protective layers, thus permitting entry of sea water or other mineralized water into aquifers.

For the country as a whole, the greatest change wrought by man has been the change from the original forest and grassland to cultivated or barren areas.

In the absence of actual records of ground-water levels in wells since the beginning of settlement, there is a broad field for argument as to the effects of the changes in vegetative cover upon ground-water storage. It is certain, however, that where the earth materials were saturated to within a few feet of the surface, the cutting of deep gullies has lowered the water table as effectively as ditches have done for numerous drainage projects.

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How We Measure the Variations in Precipitation

William E. Hiatt and Robert W. Schloemer

We talk a lot about normal rainfall, but it would be hard to find a month or a year in which the precipitation could be called normal.

Unusual as the normal is, however, we need it as a yardstick, just as we need standard measurements in agriculture and industry so we can determine, for instance, whether production is good or bad.

We need also to know the variations that we add up to make the normal—which is an average of wide differences over a long time. Floods and droughts are the direct result of departures from the normal, but minor fluctuations in the amount, time, and place of rains are of concern also to each of us.

Precipitation is measured as it falls and also after it has accumulated as snow.

The falling precipitation is caught in various kinds of gages, suited to the different situations where the rain and snow are to be measured.

There are about 10 thousand nonrecording gages in the United States—an average of three to a county. With them, observations are made daily by public-spirited citizens, who perform this important service without pay. In the nonrecording gage the rainfall is funneled into a small-diameter measuring tube, where its depth is amplified so that hundredths of an inch can be measured accurately with a simple calibrated stick.

During the snowfall season, the funnel and measuring tube are taken out of the gage, and snow is caught in the 8-inch-diameter overflow can, or the can is used to cut a core of new-fallen snow. The snow is then weighed or melted and measured in the measuring tube to obtain the water equivalent.

There also are about 3,000 recording gages, which have weighing or tipping bucket mechanisms that produce a continuous record of precipitation as it falls into the gage.

Storage gages are placed at remote sites, which usually can be visited only a few times a year. This type of gage has a large capacity, is charged with antifreeze, and has an oil film to minimize evaporation between readings. There are about 300 of these gages—most of them in the western mountains. Many of them are on towers so they will not be covered by snow. Most of them are equipped with flexible, slatted shields to reduce the effects of wind. Recent efforts to perfect unattended gages, which report automatically by radio, have had considerable success. Such gages are too expensive for widespread use, however, and precipitation usually is observed only in places where people can conveniently read the gage.

Besides the network of the national weather service, special networks of gages have been established, notably in Ohio and in Los Angeles County, for flood-control operations, studies of rainfall during thunderstorms, investigation of soil erosion, and for other purposes.

BUCKET SURVEYS often are made after unusual storms by various agencies to supplement the official but sparse network of rain gages. These readings are obtained from buckets, troughs, cans, barrels, homemade gages, and other containers. Citizens have rendered a valuable service by noting and reporting to the Weather Bureau rainfall in excess of about 3 inches an hour or 6 inches a day, times of beginning and ending, exposure conditions, and nature of the container.

Precipitation that has accumulated as snow on the ground is measured daily as to depth and water equivalent at each of 300 stations of the Weather Bureau, which are in large cities. At more than a thousand other places, mostly in the mountains in the West, the snow depth and water equivalent are measured at intervals of approximately a month in the late winter and early spring by snow surveys.

Radar is coming into use for tracking storms and for indicating precipitation rates and duration within a storm. Radar is particularly effective in localities where there are too few gages to give an indication of the areal distribution of precipitation (the average distance from gage to gage is 15 miles in the United States) but where there are enough gages to calibrate the intensity pattern indicated by radar.

The variation in precipitation catch because of differences in commonly used gages seldom exceeds 5 percent. The variation because of differences in the local site may exceed 50 percent when wind speeds are greater than 20 miles per hour at the gage. The gage is an obstruction to the moving air, part of which rises in passing the gage. The upward movement of air over the gage reduces the fall of precipitation, particularly snowflakes, into the gage. Shields attached to the gage help some in reducing the wind effect, but the best solution is to avoid windy sites.

The best sites are surrounded with good natural shelter, such as low trees or shrubs, or small buildings. A single large obstruction too near the gage is harmful because it may intercept precipitation when the wind is from its side. Because wind turbulence increases with height above the ground, a gage should be no higher above the ground than necessary to avoid spatter, runoff, or envelopment by snow.

Efforts are being made continually to improve the design of gages and standards for choosing their sites so as to achieve more nearly the ideal of true catch. In the meantime, gage catch on the average is deficient by a few percentage points, rather than excessive. By means of standard types of gages and standard rules for exposing them, however, gage catch has a reliable and practical index relation to true catch.

INTERPRETATION of the data involves estimating the time, space, and frequency of distributions of precipitation from observations at a few points.

The distribution of precipitation in time requires the use of all available data, plus knowledge of the meteorology of storms. For example, rainfall that is spotty in its distribution is likely to have variable rates at points within the area. A storm with low, steady rates of rainfall is likely to have a fairly uniform distribution over an area. The time distribution of precipitation at a gage observed only once a day can be inferred by the time distribution observed at nearby recording stations or by interpretation of the sequence of meteorological events.

The variation in rainfall over an area—on a storm, seasonal, or other basis—requires knowledge of storm movements, storm processes, and the physiographic influences on those processes. It is not enough in rugged loca-

tions merely to interpolate linearly among the station data available. Nor is it correct to assume that each station represents a large area surrounding it—say halfway to the closest stations in all directions. The record from each station represents the complex of the rainfall-influencing factors that exist at that station site. To interpolate, it is necessary to know what those factors are and how they are distributed over the area.

In mean annual rainfall, the variations in storm dynamics are usually averaged out over fairly large areas during a period of record of several years.

In some regions the areal distribution of total annual or seasonal precipitation shows remarkable consistency from year to year. In those regions the average seasonal precipitation over an area is a fairly reliable function (not necessarily a simple mean) of the precipitation observed at certain well chosen index stations.

In general, rainfall diminishes with distance from seacoast and increases with elevation above sea level. More precipitation is received on windward than on lee slopes, the variation being greatest with the steepest slopes.

Those and other parameters may be objectively defined. They operate differently in different regions, but within a region they are functionally related to mean annual or seasonal precipitation at sites having precipitation records. By means of those functions, the mean annual precipitation is estimated at intervening places where it is not observed but where the physiographic parameters can be measured. This technique has been used for refining the mean annual precipitation map for about a quarter of the area of the United States.

The longtime average rainfall for a station having a short record may be estimated by comparison with the average observed at a few nearby stations having long records and noting how the averages compare during the short record common to all the stations.

Records occasionally require adjustment because of nonstandard exposure or nonstandard methods of observation. A consistent bias can be discovered and evaluated by a method known as double-mass analysis. Yearly values of precipitation at the station are accumulated, and the accumulated totals are plotted against the corresponding successive accumulations of average precipitation at nearby stations known to have reliable records. Changes in the slope of the plotted line show the time and amount of change in the observational regime at the station being tested.

THE MECHANICS of storm precipitation determines the kind, rate, and duration of precipitation at the ground. Intense rains lead to serious erosion problems. Freezing rain and hail do direct damage to plants. Rain from light showers evaporates without material gain to crops. Long rainy periods frequently are as damaging as drought.

Precipitation is the end product in the form of rain, snow, hail, or sleet, which results from reduction of the temperature of a mass of air below its capacity to hold moisture. The excess moisture is released, and the form in which it reaches the surface of the earth depends on its initial temperature, the temperature of the air through which it falls, and the temperature at the ground surface. The intensity of precipitation at a point on the ground depends on the amount of cooling of air taking place overhead and the volume and moisture content of the air.

Most of the cool-season precipitation in the United States is associated with cyclonic storms, which develop as a result of interaction between cold and warm air masses. The classical model—with steady, light-to-moderate rain to the north and east of the center and with showery weather to the south and west—has been little modified in the past years, except for greater detail obtained from concurrent surface and upper air charts, which establish better understanding and explanation of de-

viations from the model. Some of our heaviest rains may occur in the east or northeast portions of the storm if the warm air riding up over the cold air is unstable. Also, it is now easier to delineate the expected areas of intense storminess in the southern semicircle by examination of temperature, moisture, and winds in depth.

Light-to-moderate, steady rain indicates rather uniform upglide of warm moist air over a large area. Such upglide may be associated with the warm-front rainfall in the northeastern quadrant of cyclonic storms or may be induced by the forced rise of moist, stable air up the windward slopes of mountain ranges.

Interspersed with the steady rain may be short bursts of rain of higher intensity, which result from local vertical conditions of temperature and moisture distribution suitable for the development of convective cells. Rainfall of a somewhat more intermittent character and greater intensity is associated with tropical storms or hurricanes. Except in the very center and at the outer edge of the storm, conditions are more or less uniform over large areas, so that the precipitation record represents a rather regular succession of hourly accumulations.

Rain of sudden beginning and rather sharp ending in a few hours or less is characteristic of thunderstorm or showery conditions. Generally the degree of instability and vertical speeds of processed air, as shown by the turbulent cloud masses, indicate the intensity of rainfall.

Violent overturning and successive trips of a water droplet past the freezing level result in hail.

Freezing rain, forming glaze, is the result of rainfall originating in relatively warm air aloft but freezing on contact with the ground and exposed surfaces that are at a temperature below freezing.

Sleet results from the same general conditions, except that the water droplets freeze before striking the surface.

Seasonal characteristics of storms reflect the basic relationships between rainfall mechanism and temperature changes. The intensity, frequency, and areal coverage of cyclonic storms are at a maximum during the winter, when major storms frequently invade the lower California coast and are not unusual in the Gulf States. As the warm season approaches, the intensity and frequency of cyclonic storms decrease, and the normal paths shift more and more to the north, so that by midsummer such storms are frequent only along the northern border of the United States.

In summer the invasions of cold air from the north decrease in frequency and intensity; higher surface temperatures, due to solar radiation, increase the instability of air passing over the land; and the characteristic dominance of thunderstorms begins to be reflected in the rainfall patterns. The higher temperatures during the summer months also raise the moisture-holding capacity of the air, so that when precipitation-releasing mechanisms do operate, the potential for total volume of rainfall per unit volume of air is greatly increased.

Tropical storms in their active stages and decadent tropical storms influence the southern tier of States and much of the eastern part of the United States. On the average, hurricane rainfall increases in volume during the fall. But it is not unusual for a year or several years in succession to go by without evidence of a tropical storm in a particular locality. In other years a single point may experience several such storms. As tropical storms move inland and northward, their intensity generally declines, cold air is incorporated into the storms, and characteristics become almost indistinguishable from the ordinary middle-latitude cyclones.

Snow cover is important to agriculture in several ways (for example, seasonal runoff for irrigation and winter crop cover). The amount of snow cover at a particular time is related to the frequency and intensity of snow-

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storms and the temperatures prevailing before and after it begins. The colder temperature and greater precipitation at higher altitudes encourage the accumulation throughout the winter; the occasional warm spells characteristic of most of the Eastern States tend to discourage the accumulation of great depths of snow.

Some areas (the Great Lakes and the east coast, for example) exhibit strong local effects on the weather. When very cold air moves across the Great Lakes in the fall and early winter the lower layers of air are warmed rapidly and pick up considerable moisture by evaporation from the lake surface. On the downwind shore, particularly if there is a little rise in the ground, instability showers may occur for several days.

The deep snows of winter along the south shore of Lake Erie and Lake Ontario are noteworthy. There is the reverse tendency, inhibiting precipitation in the spring, although not so marked as the winter influences. The high water temperatures off the east coast during the cool season and the southeastward-moving cold air from the continental interior provide a large temperature contrast and source of potential energy. Frequent cyclonic development or redevelopment takes place just off the coast, and the influence of such storms is felt along the seaboard States.

THE APPLICATION of observations of precipitation to the many facets of the development of our water resources requires considerable processing and interpretation of available data before a practical use can be made of them.

Normals of precipitation are a basic requirement for planning, because early indications of success or failure of a planned project can often be obtained from a study of them. The Weather Bureau has completed the determination of monthly and annual normals for regular stations.

Applications of data on rain and snow to decisions on day-to-day farming operations are well known. Also well known is the use of weather data—averages and frequencies—in longer range and larger scale planning. Studies of past records provide a basis for estimating the probability of adequate rainfall for crops and pastures in areas where chances of drought must be reckoned with.

Coordination of the varied aspects of the water resources of the large river basins requires climatological investigations of a much more complicated pattern. We give some examples of special interpretations and uses of data to illustrate the wide variety of applications.

Comprehensive studies of depth-duration-area relationships in major flood-producing storms and their relation to concurrent meteorological conditions have been in progress since about 1935. The studies are used in conjunction with planning and design of flood-control structures, storage reservoirs, and multiple-purpose projects.

For the very large multiple-purpose structures, whose failure would cause great property damage and loss of life, meteorologists estimate the probable maximum rainfall and snow-melting rates. For smaller structures, such as erosion-control spillways or culverts, where it would be uneconomical to design for the maximum since occasional overtopping would do little harm, the design is intended to accommodate a fairly infrequent flow like that occurring once in 5 years or so. Precipitation data are often necessary for estimating streamflow probabilities and extremes.

An important use of precipitation data is in streamflow forecasting. Flood forecasting, particularly in headwater reaches, is based on reports of prior rainfall, more recent rainfall, and snow cover. A different type of forecast is the forecast of water supplies. The Soil Conservation Service and Weather Bureau cooperate in preparing and issuing forecasts of volume of streamflow for several months in advance for irrigation and other purposes. The

forecasts are based largely on observations of autumn rainfall and winter gage catch or snowpack or both.

The rainfall-runoff relations, derived initially for forecasting, have other applications. By means of such relations, based on relatively short records of streamflow, a synthetic streamflow "record" can be extended as many years as available rainfall records permit—often longer than 50 years. Rainfall-runoff relations are necessary in appraising the effects of changed land-use or water-management practices. So-called natural-flow forecasts, based on prestructure relations, are made currently in several places to evaluate the effects of the operation of reservoirs.

The incidence of the short-duration rainfall (the hourly amount, say, that would be equaled or exceeded once in 10 years) can be estimated for localities where there are no short-duration rainfall data by proper interpretation of the available data. Relations may be derived for stations having recorder data, relating hourly intensities to daily intensities, mean annual rainfall, mean annual number of days of rain, and other parameters. Those relations are then applied where only the common climatological parameters are observed.

Between the specialized estimates at one extreme of the use of rainfall data, and the other extreme of simple day-to-day decisions that are so taken for granted we seldom reflect on them, there is a large area of application available to untrained persons if they know what facts are available.

Every week the Weather Bureau publishes the Weather and Crop Bulletin, which summarizes recent weather and crop developments for States and the country. Monthly summaries of climatological data contain precipitation and other data for all United States stations, by States. Each regular weather station prepares an annual local climatological summary, which contains averages, totals, and extremes of the important weather elements for the year and for the period of record of the station.

Each month from January through May the Weather Bureau publishes water-supply forecasts for about 500 stations in the Western States. In *Climate and Man*, the Yearbook of Agriculture for 1941, are many tables and maps that represent probably the most complete weather summaries generally available. The Weather Bureau (which was a part of the Department of Agriculture when *Climate and Man* was published) is extending them and bringing them up to date. All those publications and other data are available for public use at any Weather Bureau office.

Perhaps no other single item determines a profitable or unprofitable crop year (except under irrigation) more than the timing and amounts of precipitation as related to the planting, growing, fruiting, and harvesting of each crop. But the dependability of precipitation has been investigated in a rather hit-or-miss fashion according to its relation to characteristics of specific crops.

Knowledge of observed intensities of point rainfall, of particular value in evaluating problems in connection with local drainage, have been tabulated for 24-hour amounts (Weather Bureau Technical Paper No. 16) for all Weather Bureau and cooperative stations. Maximum observed 1-, 2-, 3-, 6-, 12-, and 24-hour amounts at recording stations have been tabulated (Weather Bureau Technical Paper No. 15) for several Western States and almost all of the east-coast area. Most data on distributions and frequencies of point rainfall have been published as miscellaneous papers in scientific periodicals (many of which are listed in American Meteorological Society Bibliography). A good example of station analysis is *The Climatic Handbook for Washington, D. C.* It is expected that the use of punchcards will expedite the program of analysis of climatic data of this sort.

Although most precipitation falls as rain and rain is usually of chief interest, other phases of precipitation have great importance at times. Examples are damage caused by hail and by freezing rain. Early winter snow cover helps insulate the underlying soil, but late melting of the snow retards spring plowing and planting. The Cooperative Snow Investigations of the Corps of Engineers and the Weather Bureau has improved our understanding of the physical properties of snow—how fast it melts under various weather conditions and how rain or snow is retained or transmitted. Studies of records of snowfall and accumulation have given builders and others yardsticks for measuring snow loads that buildings can carry and for designing and using equipment for melting and removing snow.

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The history of every nation is eventually written in the way in which it cares for its soil.—FRANKLIN D. ROOSEVELT

Is Weather Subject to Cycles?

Ivan R. Tannehill

Droughts and floods often cause us to think about possible cycles, rhythms, and trends in the weather.

Daily and yearly changes in rainfall are obvious and were recognized long ago as caused by the motion of the sun and the consequent variations in temperature and wind. The first world travelers learned that in some places rain falls at about the same time almost every day. Then, too, in many regions dry and wet seasons or other variations in the rainfall are more or less regular every year. The knowledge of some of those phenomena has encouraged a search for cycles.

In most land areas the daily and seasonal variations in the rains are not very regular or dependable. (In this discussion rainfall includes snow and other forms of precipitation.) The dry and wet spells come at irregular intervals. In many regions a succession of years or seasons drier than normal followed by an extended period of wetter weather is common. Rainfall in the amounts adequate for agriculture usually is more dependable on the lands near the sea. As we go inland it becomes less regularly so, until we reach the deserts and arid regions. There are exceptions, however, for which the causes are obvious. The deserts of Peru, for instance, are close to the ocean, but the moist sea winds are relatively cool and stable and acquire no upward motion. Little or no rain results, for atmospheric processes are such that rain must come from air that is being cooled in one way or another. Mountainsides facing the sea, with moist winds blowing upward and becoming cooled, have plenty of rain, while on opposite slopes the air is warmed in descent and becomes dry even if it is not far from the ocean.

Thus for many reasons the daily and seasonal rhythms in rainfall are imperfect. At times they cease altogether. In this respect rainfall is more difficult to predict than temperature. Daily and yearly variations in temperature are fairly regular, although marked changes result occasionally from large horizontal motions of the atmosphere. As a rule, the temperature is high in the afternoons and low in the early mornings, lagging after the sun, but in middle and higher latitudes the temperature on any one night often is warmer than during the preceding or following day. Summers range from cool to hot and winters from mild to very cold, depending on broad-scale motions in the atmosphere. In more complicated ways and in greater frequency than temperature, rainfall departs widely from normal or average daily and seasonal patterns.

The great economic importance of variations in rainfall in some parts of the world has induced many investigators to look into cycles for an answer to long-term forecasting.

In a review of many claims, one British meteorologist counted more than 130 different cycles of which one or more investigators had found evidence in the weather records. Many more have been indicated by tree-ring measurements and other data. It is probable that no matter what happens in the rainfall it can be made to fit one or more of the numerous cycles.

Aside from the daily and annual periodicities, cycles can be divided into two classes. First are those derived from the records without any explanation of their causes. In this group are many that run for so long a term of years that no acceptable verification is possible at present. Others, derived from analyses of shorter periods, persist for a time and then fail altogether or are reversed in phase.

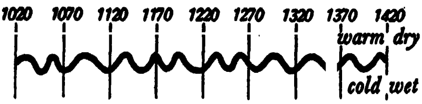
One of the most notable was the 35-year cycle named after its author, Eduard Brückner, a climatologist in Vienna. The cycle, based on rainfall records from 1815 to 1890, averaged 35 years but was quite variable within the limits of 20 to 50 years. He also showed evidence of such a cycle in the years 1020 to 1420, based mostly on records of severe European winters. Brückner's cycle became well known in later years, but the variation in rainfall is small and too irregular to be of definite value in prediction.

Nearly all persons who engage for a year or more in predicting weather from maps find now and then that the current map looks a good deal like some preceding map. If the forecaster has a file of back maps or an index to them he can refresh his memory. Sometimes, but not very often, the resemblance is good, and the development of the weather seems to have been much like that in the current case. The back map is called an analog.

For this purpose the maps over a long period must be cataloged so that the forecaster can classify the current map—much as a fingerprint is classified—and find similar maps at the same season in other years. In tests covering 40 years of maps, many analogs have been found, but only a few can be called excellent. The advantages of the method seldom justify the time required, and it has not been used as standard practice in many forecasting offices.

That points to the probability that there are no clear-cut cycles or rhythms in the weather. Nevertheless, at intervals, a surprisingly good forecast is made of an unusual development in the weather because of the forecaster's recollection of a similar case, sometimes many years before.

In the second group of cyclical variations are those for which a motivating force has been suggested but the processes in the atmosphere that lead from cause to effect cannot be explained. The moon, for example, appears to influence weather, but no one can explain how. Other forces of the same kind have been suggested (and some of them may possibly be real), but doubt centers around the lack of a satisfactory explanation.



Eduard Brückner's weather cycle for the years from 1020 A. D. to 1420 A. D. It is based mostly on records of the severity of European winters. (After Gregory.)

Another group of variations in the second class is attributed to solar changes. Attempts are made to show how the varying energy from the sun causes the changes in the temperature and the circulation of the atmosphere that seem to account for certain cyclical patterns in rainfall. While the solar hypothesis is more acceptable on a physical basis than many others, it suffers in two ways. For one, the circulation of the atmosphere and its variations are complex, and the effects of solar changes are extremely difficult to trace. In fact, no acceptable theory explains fully how solar effects are converted to changes in the weather.

In another respect, the usefulness of conclusions derived from the solar hypothesis has been questioned, for the changes in the sun are not regular.

THE SUNSPOT CYCLE, which averages approximately 11.3 years, has been as short as 7 years and as long as 17 years. We have yet no generally accepted method of predicting solar variations so that the resultant weather changes can be foreseen in any detail.

Through millions of years of geological time, unquestioned evidence appears of great oscillations in world climate, and several hypotheses have attempted to explain them. In the case of oscillations within historical times, however, the evidence points to two probable causes—the effect of dust thrown into the atmosphere by volcanic eruptions and the effect of the sun's radiation. Only the latter is cyclical in nature.

Weather has other rhythmic or recurrent features. The atmosphere over a hemisphere or a large part of it may exhibit a certain resonance. The change in temperature that comes with a single rotation of the earth on its axis may not be sufficient to start a large-scale motion in the atmosphere, but the accumulated effect of heating and cooling in a number of successive rotations may find a resonance in the atmosphere over a region and a periodic change may set in. That can result in rain every fifth day or every seventh day, or at some other interval, continue that way for a month, more or less, and then cease.

In large areas of the United States an interval of 4 or 5 days is the most common and persistent between rain-bearing disturbances. That fact is not very useful, however, unless the associated motions of the weather systems are watched on a map of the hemisphere or a large part of it.

Research in the upper air has shown a vast wavelike motion in the horizontal circulation of the atmosphere above the earth. Large-scale features of this circulation around the hemisphere change occasionally, but any given pattern tends to persist for a time, bringing a characteristic disturbance of rainfall to the lands below. The high-level winds over the United States in recent dry years, for instance, have some of the same characteristics as those in the dry years of the 1930's.

Some scientists believe there are vast oscillations between distant parts of the atmosphere whereby one may say, for example, that unusual weather in one world region in December may indicate or foreshadow dry weather somewhere else in the world the following month. Tremendous tasks in correlation of pressure, temperature, and rainfall for selected places around the world for succeeding months or seasons have been carried out, but they have not yielded much that is definitely useful. There has been more "cause-and-effect" weather forecasting by this type of foreshadowing, however, than by any other method. Nevertheless, the reasons advanced for the existence of the correlations are rather vague.

Other weather phenomena of the recurrent type are known as singularities. They are the spells of warmer or colder or wetter or drier weather than normal for the season that develop at certain times each year. The Northeastern States, for example, have their January thaw and Indian summer. Similar spells of weather are known in Europe. Winter storms in some parts of Europe tend to recur at the same time each year. Such spells and recurrences undoubtedly have a physical basis. Hurricanes occur mostly in the same months each year; therefore it must be true that the ocean heat, lagging behind the more rapid changes of temperature on the continents, is a major cause of hurricanes. But to the extent that that is true, hurricanes are merely a part of the annual cycle.

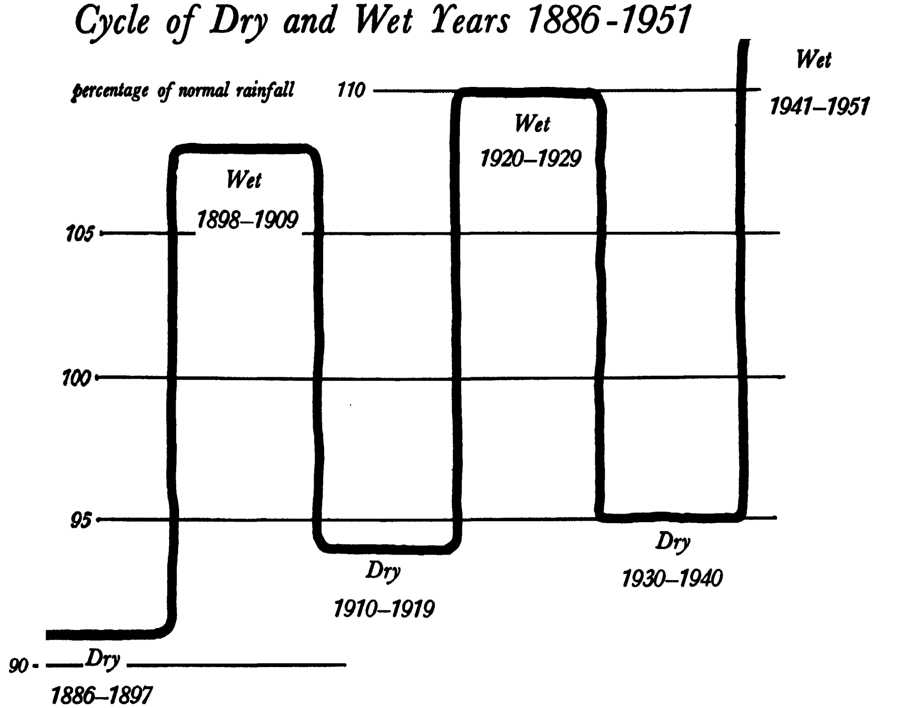
As we look through the literature at the amazing amount of work that has been done on so many phases of this question, we come to one definite conclusion—the problem is complex and any apparent cycles or rhythms that appear for a time in the rainfall records must be looked upon with suspicion.

Even if the so-called cycles or rhythms are demonstrated on a sound physical basis we are nevertheless, for another reason, forced to exercise a great deal of caution. There are long swings or trends in the weather, such as the rise of temperature in some parts of the world in the present century, recently so noticeable in winter in eastern and northern parts of this country and most pronounced in some Arctic regions. As this trend becomes dominant, a local rhythm or periodicity that depends in part on the recurrence of cold winters may gradually diminish and finally fade away or shift to higher latitudes. On the other hand, accurate weather records are generally too short to determine the nature and cause of the so-called trend or judge its future course. It is quite possible that long-term progressive changes in rainfall climates are cyclical or rhythmic, but of such long periods that our records do not reveal the facts.

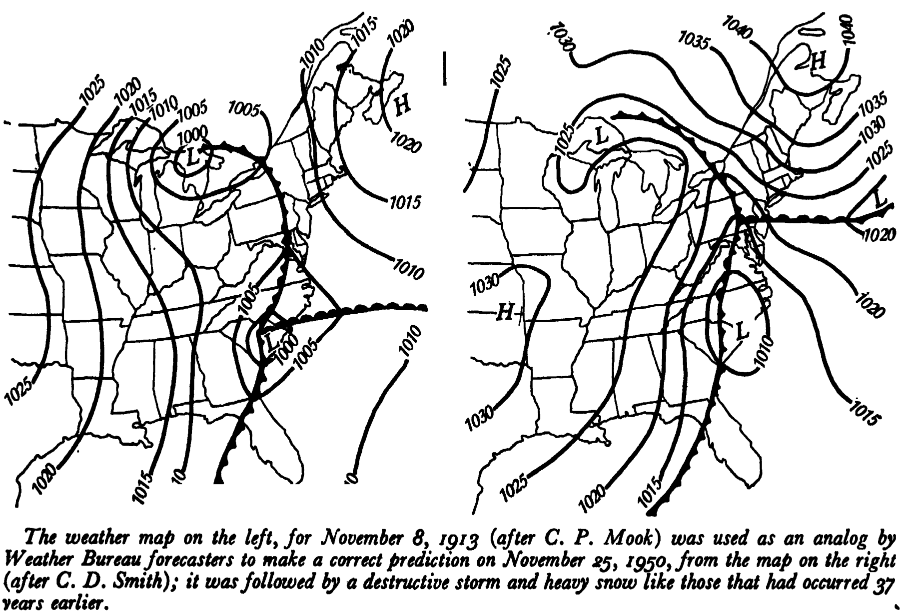
As world populations increase, some parts of the problem assume tremendous importance. In the United States the rainfall climates range from the superhumid in some Eastern and Southern States to the dry climates of large regions in the West and Southwest. We deal with the problems in various regions by irrigation, drainage, flood control, soil conservation, and similar practices. In a vast region, however, where rainfall normally is adequate for agriculture (though barely so in some marginal areas) it is so variable that frequently extremes cause minor or major disasters. In some degree, the situations are made more dangerous by man's actions, such as cultivation and denudation, which eliminate a part of Nature's stabilizing controls and contribute to disaster, at least in local areas.

THE METEOROLOGIST struggling with these questions adopts one or two general lines of attack, depending on his ability to understand what is going on or to extrapolate from the tendencies, trends, or rhythms apparent in the records. In neither case is he on very solid ground, but two phases of the work are definitely promising.

First, the broad-scale patterns of the atmospheric circulation tend to persist or to change slowly and to afford useful correlations with the main features of weather at the surface of the earth. In this work the meteorologist endeavors to extend his view more than 30 days into the future. He must have an intimate knowledge of the impact of change in one region on remote regions. For example, at certain critical times in the year, the patterns are apt to change, and a constant watchfulness sometimes yields deductions very useful for planning in agriculture and industry. Here the meteorologist has some background of experience because his predecessors, beginning in the latter part of the 19th century, originated the concept of "centers of action" as applied to surface weather conditions around the earth. They watched the



Cyclical pattern in Oklahoma rainfall. The total rainfall for each group of years given within the diagram is shown in percentage of normal. Each group of years begins 3 years before sunspot minimum. The present group, presumably 1952–1962, is running very dry, in accordance with this large-scale cycle.



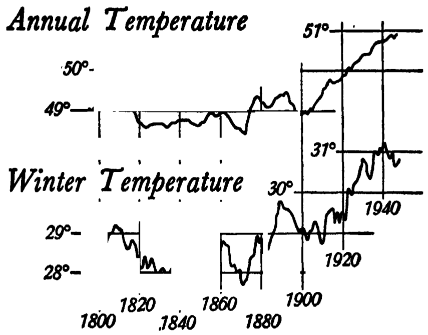
The weather map on the left, for November 8, 1913 (after C. P. Mook) was used as an analog by Weather Bureau forecasters to make a correct prediction on November 25, 1950, from the map on the right (after C. D. Smith); it was followed by a destructive storm and heavy snow like those that had occurred 37 years earlier.

centers (for example, the continental highs, the Aleutian and Icelandic lows, the oceanic high pressure cells) for hints as to future weather beyond the day-to-day predictions in certain regions. More recently the meteorologist has learned why the centers of action behave as they do in relating them to the upper planetary waves.

About 15 years ago meteorologists in the United States introduced the idea of the zonal index, a measure of the speed of the westerly winds in middle latitudes as a part of the general circulation. When the pressure increases from north to south in this belt, the index is "high"; when it diminishes from north to south in the same belt, the index is "low." More recently it has been shown that there is a variation in the index that is not regular; it is called the index cycle. The time interval is 4 to 6 weeks. The zonal index is related to the form of the general circulation of the atmosphere and especially to the position and development of the centers of action. In turn, the weather, including rainfall, is related to the changes in the index, but the cycle is irregular and, as in the case of most other so-called cycles in weather, the meteorologist has been unable to predict the changes in the index with satisfactory accuracy.

In the second phase, the meteorologist attempts to associate the weather with solar activity, to find an adequate measure of the variations in the latter, to trace their effects through the atmosphere, and to explain the results in terms of weather changes, including anomalies in rainfall. Here there is hope of further progress as man's understanding of solar changes increases and information regarding the atmosphere is improved through balloon soundings and rocket research.

There is some evidence of important effects, such as long-term, large-scale migrations of rainfall toward the interior of the United States that result from high solar radiation and migrations to coastal areas when radiation is low. The results are similar to the annual mi-

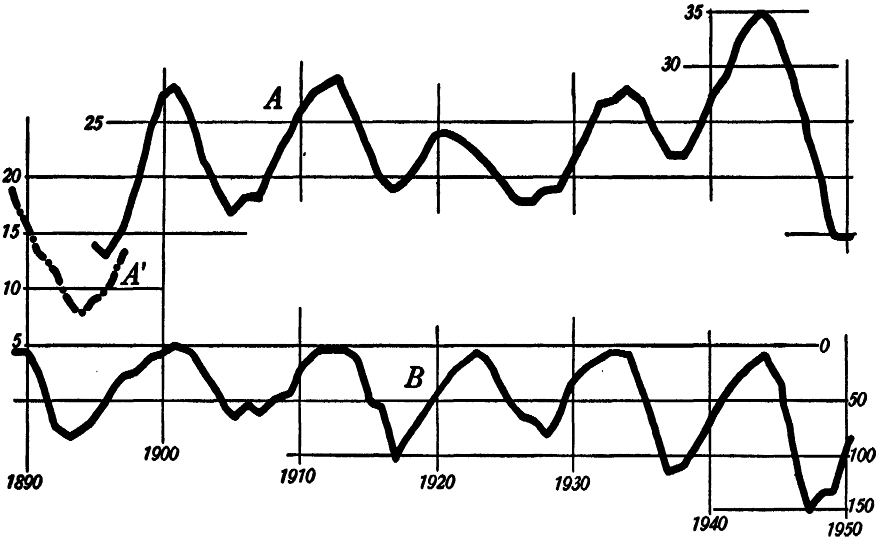


Upward trend in temperatures at New Haven, Connecticut, shown by 20-year means ending at the dates given.

grations that attend seasonal changes in insolation. Then, too, there are indications of shifts of rainfall from warmer months to colder and back again as radiation increases and decreases. The total evidence accumulated in the past 100 years to show important solar effects cannot be disregarded. Combinations of these rhythmic variations provide an index to long-term changes in rainfall, but at present it seems reasonable to conclude that the practical results in the immediate future will be limited to a very general indication for the few years ahead, useful for planning but not yet applicable in any detail to the prospects for a single season or even a single year. In this phase the work of the meteorologist will depend in a large degree on the ability of the astrophysicist to predict long-term and short-term changes in solar activity.

For the reasons given, it has not yet been possible to bridge the large gap between the projection of current atmospheric patterns into the future for 30 days, possibly more, and, on the other hand, the detail which can be derived from the analyses of the long-term effects of solar changes. But there is much hope that the meteorologist will be able to make more rapid progress as we accumulate more information about the upper air.

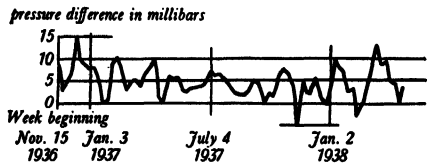
An enormous amount of work on cycles in rainfall and related problems



A, Differences in yearly rainfall between Galveston and Amarillo, Texas (smoothed); A', Abilene rainfall is used for years prior to beginning of Amarillo record. Scale at left shows excess of Galveston rainfall over Amarillo's in whole inches. B, Annual sunspot numbers inverted by scale at lower right. This cycle shows migration of rainfall from coast to interior and back again.

has been done, but in an unorganized fashion by men who were depending on some other activity for a livelihood.

The main reason is that years ago scientists reached a rather definite conclusion that there are no true cycles in rainfall. It is believed that there are only certain rhythmic variations which can and must be dealt with on a physical basis as soon as there is a much improved understanding of the complex changes that take place in the earth's atmosphere as a result of its own internal reactions and the impact of extraterrestrial forces. Some useful progress has been made toward an understanding of the physical processes involved rather than dependence on cycles or rhythms as such. And, in any case, whether the investigator depends on one or the other of these methods, it has become certain that he must use weather maps to get 3-dimensional views of the atmosphere for the time involved, whether they represent means for a week, a month, or for one or more years. On this basis the meteorologist is making slow but definite headway.



Examples of variations in weekly values of the zonal index—pressure differences between 35° and 55° latitude—in millibars, scale at left. The higher the value the stronger the westerly winds in middle latitudes.

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Hauling Down More Water From the Sky

Chas. Gardner, Jr.

There is a river in the sky—a complex, swirling, tumultuous river of air and water.

Sometimes we cannot see the water, when it is in the form of vapor. At other times, airborne droplets of water gather in clouds, which, of course, can be seen. We should not assume that clouds contain water and the surrounding air does not, because the surrounding air carries vapor, which often flows into the cloud. And, also, clouds dissolve into vapor and fade away. But the clouds we see with our eyes contain water brought along a step in the process of becoming rain.

With clouds we can have rain. Without clouds we cannot.

But with clouds we do not necessarily have rain. The droplets of water often fail to take the further step of becoming raindrops, accretions of water heavy enough to fall to the ground.

This exasperates the farmer—when lush clouds, apparently containing a great deal of moisture, float over his dry fields and fail to precipitate out even one small part of the moisture carried by and flowing into these clouds. Cloud census studies have shown that seasons with considerable cloud cover can also be dry seasons.

Why? Can we coerce the droplets into becoming drops heavy enough to fall onto the ground? Can we haul down needed moisture from the sky?

A FEW YEARS AGO many of us thought we had the answer. For some time it had been theorized that minute particles of dust, present throughout the atmosphere, were a necessary ingredient of rain, something for the droplets to cluster on and grow. In 1946 Dr. Vincent J. Schaefer, of the General Electric Co., sprinkled particles of dry ice from an airplane and produced precipitation. A little later Dr. Bernard Vonnegut of General Electric ran onto silver iodide as the ideal particle or crystal. A few experiments produced seemingly awe-inspiring results.

And so, "scientific rainmaking" came into being. The scientific basis of it was "artificial nucleation"—that is, the supplying of artificial nuclei or particles to clouds thought to lack sufficient natural nuclei.

A comment on terminology should be inserted at this point. The word "rainmaking" seems to imply the creation of water, whereas so-called rainmakers cannot produce water that does not already exist in the air. Perhaps "rain increasing" should be used. Further, the phrase "weather control" implies a management of the elements beyond present conception. Perhaps "weather modification" states more accurately what we can now visualize. The terms "rainmaking" and "weather control," however, have become common and are more easily recognized.

Artificial nucleation is tied in with the ice crystal theory. According to the theory, natural ice crystal formation occurs at quite low temperatures (−40° F.). Presumably the crystals grow by attracting other moisture particles until they become heavy enough to fall out of the clouds as snow, which melts on the way down and becomes rain.

Dropping dry ice (carbon dioxide) on clouds cools areas of those clouds and starts the process of crystal formation. The effect can be substantial if the clouds are near the temperature at which ice crystals form naturally.

Supplying nuclei to clouds does not cool them, but with nuclei the ice crystal formation occurs at higher temperatures—that is, below freezing but closer to the freezing level. Some natural nuclei or dust particles start the process at temperatures between −40° and 5°. But crystals of silver iodide (artificial nuclei) start it between 5° and 25°.

Therefore, silver iodide not only can

start rainfall in clouds too warm for natural rainfall production but can increase rainfall in clouds already producing small amounts by nucleating the warmer lower sections.

Another method of producing rainfall is of interest, although not of commercial importance. In warm regions, nonfreezing clouds release rain, obviously by some other process than the formation of ice crystals.

It is commonly believed that precipitation results when larger than normal water droplets fall relative to other droplets, collecting enough smaller ones to grow to raindrop size large enough to fall out of the cloud. The answer lies in providing the larger droplets.

Such clouds, found in the Southern States and farther north in the summer, have been successfully seeded by water sprayed from airplanes.

But airplanes cost money to operate and flying them into storm clouds can be dangerous. The large commercial "cloud-seeders" therefore do not use dry ice or water but rely on silver iodide, which can be released from ground generators. The minute crystals drift away from the generators and presumably get sucked into the updrafts of storm clouds.

ARTIFICIAL NUCLEATION has had a big impact on the Nation, particularly, but not exclusively, in the West, where more water is almost always desirable. To those who have studied the economic aspects, it seems elementary that the Eastern and Southern States can reap more benefits dollarwise from rainmaking—if it works as some experiments suggest it may—than the dry areas of the Southwest.

During a recent year the "target areas" of scientific rainmakers in this country comprised 13 times as many acres as those under irrigation. One study showed that 20 percent of the Nation's area was covered with rainmaking efforts.

The estimates are rather haphazard and perhaps misleading, but they do suggest that rainmaking is a pretty big business, even with its uncertainties.

A recent survey of the Advisory Committee on Weather Control, a temporary Federal agency set up to "find out who is doing what, and with what results," revealed that 13 States had already passed legislation having to do with rainmaking. Eight States had legislation pending.

Most of this legislation has assumed that the rainmakers really have modified the weather significantly—an assumption that a majority of scientists familiar with the subject do not go along with wholeheartedly. Most of them seem to agree that nucleating agents can modify weather in certain circumstances. Some think these circumstances occur frequently enough so that man can change the whole pattern of water distribution in the United States, with a tremendous impact on the economy. Others are skeptical of large-scale effects. Most of them say: "A lot more has to be learned about the rainmaking process before we can tell."

Anyway, it is of interest that five legislatures, composed mostly of practical laymen, have proclaimed their States' sovereignty over the atmospheric moisture floating above their States. Those legislative bodies have shown concern over the possibility that the other States might somehow steal moisture that rightfully was theirs.

THIS IS THE ROBBING-Peter-to-pay-Paul argument that has loomed large in the minds of many people in the West. They believe that rain increasing in upwind areas must necessarily mean rain lessening in the downwind areas. People in the Southwest who have suffered from droughts these past years have taken this argument to heart.

The rainmakers answer the argument by saying that Nature is an inefficient rainmaker, with only about 1 percent of a cloud's moisture falling to the ground in an ordinary storm. By supplying more nuclei they may increase this efficiency up to 2 percent.

Such amounts are insignificant, they say, and the vast streams of moisture floating in the sky will replenish the clouds almost immediately.

Whatever the merits of this, rainmaking, viewed on a grander scale, may indeed increase substantially the amount of mineral-free water available for man's use.

FOR ONE THING, it seems perfectly obvious that many airborne streams of moisture escape the land and give much of their water back to the seas. Rainmaking might make it possible for us to take better advantage of the rain potential of these airborne streams before they get away. For another thing, it has been suggested that precipitating moisture out of clouds at earlier stages of storm development might speed up the hydrologic cycle and establish a new rainfall regime. This would mean more use and reuse of airborne moisture.

But even if rainmaking could not increase the net amount of moisture on the ground, it might yet affect the distribution of this moisture in such a way as to produce tremendous economic benefits.

DOES IT REALLY WORK? That is the question farmers ask. Scientists reply that it does in certain circumstances.

Seeding with dry ice and water admittedly has modified clouds and has produced precipitation. Silver iodide can do the same.

But scientists disagree as to whether the more economic method of seeding clouds by means of ground generators has produced, or can produce, the substantial increases in rain and snowfall claimed by the private "cloud-seeders."

The problem of evaluation is inherent in the ground-generator method. Seeding with dry ice or water, the operator can usually turn around and see the results. The seeded clouds often change form and precipitation falls before his eyes. But when he releases silver iodide from a generator he cannot see the material. Does the generator produce the right-sized crystals? Do they get into the storm clouds in the right quantities at the right altitude? Does the silver iodide retain its effectiveness or does it decay because of temperature, pressure, or exposure to ultraviolet rays. There can be many a slip twixt the cup and the lip.

The fact that he seeds during storm situations, usually when at least some rain falls naturally, makes visual observation impossible in most cases and makes measurement of any manmade increase extremely complicated.

And so, instead of seeing the cause and effect, he has to guess. And he has to attempt a measurement of the manmade increase by means of statistical evaluation. He has to compare the "target area" rainfall with rainfall of past years or, more commonly, with rainfall received in adjacent areas.

Statistical analyses—usually provided by the cloud-seeder himself and imperfectly understood by the layman—can often show spectacular and convincing results. But sometimes other persons can work over the same figures and get different results. And sometimes the statistical people can bury good results in a pile of figures. Thus the controversy.

The analyses themselves get complicated, but the problem of analysis can be stated quite simply.

When the target area gets more rain than outside areas, say three control areas labeled "A," "B," and "C," the cloud-seeder usually satisfies his clients. Yet the center of a storm may have passed over the target area to produce the result naturally and the cloud-seeder may have done nothing.

When the target area gets more rain than A and B, but less than C, the clients may nurse a small doubt or two. And when the target area gets less than A, B, and C—then they become skeptics. Yet in both cases the cloud-seeder may have increased rainfall on the target area over the amount which would have fallen naturally.

Rainfall results in the target areas

usually fall within the realm of historical variation. We can always suspect, therefore, that increases are only accidental. If we only knew how much rain would have fallen naturally, we could evaluate perfectly. This we can never know and we have to satisfy ourselves with a statistical substitute.

Failure to understand this problem leads to confusion. Many farmers become enthusiastic believers; others, confirmed skeptics. The experimental work financed by farmers and ranchers proceeds, therefore, on an uneven and haphazard basis and does not provide a great deal of data of value in determining the actual, overall results. To avoid dealing with large groups with some conflicting interests and opinions, some cloud-seeders perform work only for corporations, particularly public utilities that produce hydroelectric power. But farmers continue to support projects, principally because cloud seeding costs only pennies (5 to 10 cents an acre usually)—while added rainfall means dollars.

A STUDY of an entire river basin in the United States, based on physical assumptions considerably more modest than some cloud-seeders have asserted, showed a benefit-cost ratio of 20 to 1. Obviously experiments in certain areas—possibly mountain areas where air movements should naturally lift the silver iodide smoke into the clouds and where temperatures should be more favorable—these should show a higher benefit-cost ratio. Experiments in some areas should prove to be more nearly marginal.

Experiments in the United States have attracted a great deal of interest in foreign countries. At least 26 countries, on every continent except Antarctica, have carried out experiments in recent years.

Farmers in South Africa have used rockets to disperse silver iodide at high altitudes, the purpose being to reduce hail damage. Farmers in the Bayonne region of France have used ground generators for the same purpose. The theory of hail prevention is that, by precipitating out moisture at earlier stages, cloud seeding can prevent large hail-producing storms from developing. The same theory applies to lightning prevention and thus has interest for those who have responsibility for fighting forest fires. Some cloud-seeders in the United States like hail-prevention projects because while farmers do not always want more rain they almost always want to prevent hail if they can. Thus such projects sometimes get a steadier financial support.

Formosa and Sweden have undertaken projects to increase hydroelectric power. Owners of sugar plantations in Cuba have financed rain-increasing projects despite an average of more than 60 inches of rainfall a year. Additional rainfall means additional sugarcane for them.

Much of the work in foreign countries has been of high caliber. But it still has not supplied the answers.

RECOGNIZING THE PROBLEM of evaluation, the Congress created an Advisory Committee on Weather Control, which began work on July 1, 1954. Senator Francis Case of South Dakota and Senator Clinton P. Anderson of New Mexico, a former Secretary of Agriculture, the principal authors of the bill, started pushing for legislation in 1950.

The Advisory Committee, a temporary Federal agency, was directed to "study and evaluate public and private experiments in weather control" and to recommend the extent to which the United States should "engage in, experiment with or regulate" weather control activities. The Congress set June 30, 1956, as the date for submission of a final report.

Why a Federal committee? For one thing, the Congress felt it could make an independent and impartial evaluation, free from any bias which could be alleged, rightly or wrongly, against the evaluation of the cloud seeders. For another, it could survey the whole field of experiments, not just one or a

few. The law provided authority to demand reports from the seeders.

Analysis of experiments will produce some answers helpful to farmers and other water users in deciding whether weather control activities are a good bet or not. But the real and positive answers will come from further research into rainfall processes. The sky is a wild, unpredictable laboratory; research in weather is difficult and often frustrating. All the same, science moves inexorably onward, learning more and more about the possibilities for modifying or controlling weather.

Perhaps these possibilities will narrow down to certain limited applications. It is conceivable, though, that weather control can become a regular feature of crop production.

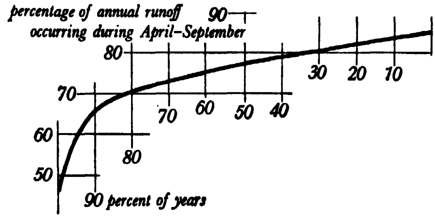
CHAS. GARDNER, JR., *became executive secretary of the Advisory Committee on Weather Control in 1954. He previously served as executive secretary to the South Dakota Natural Resources Commission. He is a graduate of Yankton College, the University of Missouri, and McGill University, and has studied at the University of London.*

Measuring Snow To Forecast Water Supplies

R. A. Work

A large part of the annual flow of the rivers in our Western States is delivered in spring and summer. That is because precipitation on the high, mountainous watersheds falls mainly as snow, and as snow it is held through the winter until springtime warmth melts it and releases it to the valleys below.

Elsewhere in the West the ratio of seasonal flow to total annual flow is always high, but it varies from stream to stream or from year to year on the same stream. That makes essential the forecasting of the seasonal flow, which usually occurs in April–September, the period of least—or no—rainfall and the season of greatest need for water for crops. It also is the time when snowmelt may cause widespread destructive floods.



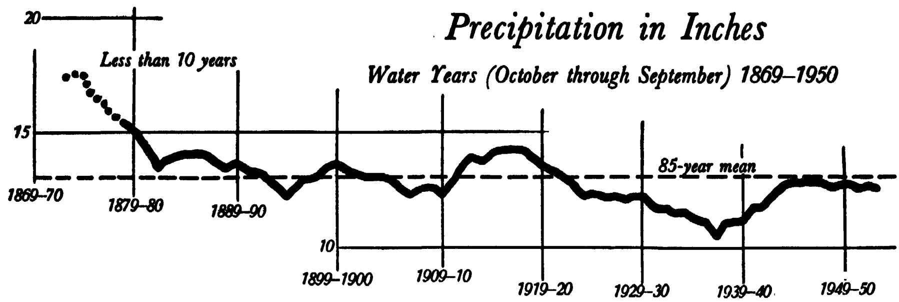
This graph shows the relationship of the seasonal flow (April-September) to the total annual flow (stream year of October-September) for a typical western snowfed stream—the South Fork of Ogden River, measured near Huntsville, Utah. The stream is used extensively for the irrigation of small farm units. In 50 percent of the years, more than 75 percent of the total runoff occurs during the irrigation season—April-September. The recorded seasonal delivery historically ranges from 45 to 88 percent of the total annual runoff.

TO MEASURE THE AMOUNT of snow on the watersheds and thereby foretell the flow of rivers months later, snow surveys are undertaken in the western mountains. The surveys were developed originally to forecast the seasonal supply of water for irrigation. They have become tools for better water management by industry, power companies, municipalities, flood control agencies, conservation agencies, fisheries, wildlife organizations, and others.

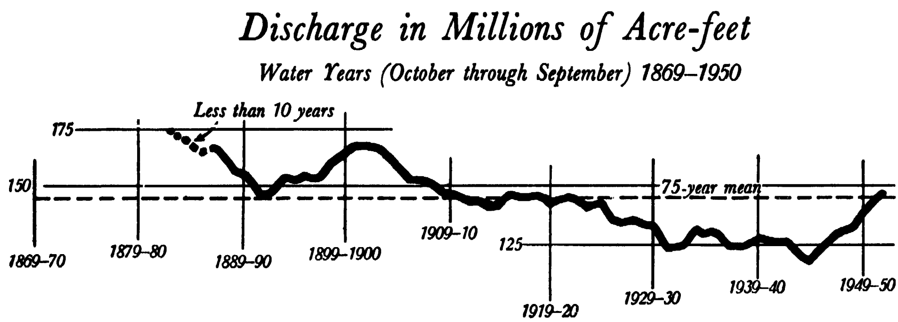
Records, history, and the growth of the West give other reasons for this important work.

Our records show that precipitation (and runoff) may depart markedly from the mean in any year or by smaller amounts for a connected series of years. For periods of 20 to 30 years or more, the general pattern of precipitation for a locality or a basin might remain nearly continuously above or below the recorded mean.

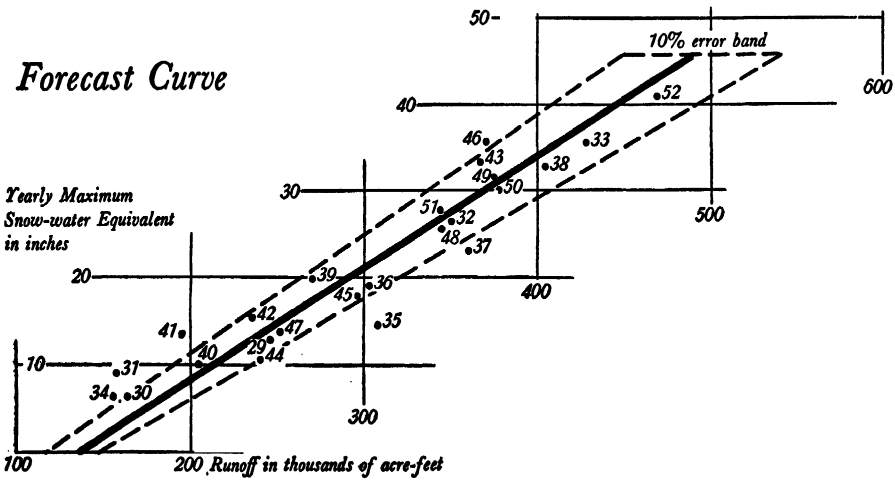
The accompanying graphs of annual precipitation for the stream year (October-September) and of the an-



The annual precipitation for the stream year (October-September) recorded at Boise, Idaho, by the United States Weather Bureau is plotted here as a 10 year running average.



Annual runoff for the Columbia River at The Dalles, Oregon (the longest continuous runoff record west of the Mississippi), plotted here as a 10-year running average, corrected by the United States Geological Survey for upstream consumptive use, is shown here for the record period.



The yearly value used for the snow-water equivalent is the maximum water content accumulated in the snow pack for the entire winter. The resulting line of best fit becomes more reliable with the entry of new records each year.

nual runoff for the Columbia River at The Dalles, Oregon, indicate that during the past 75 years there has been a trend toward lower precipitation and lower runoff in this sprawling river system, although in recent years there has been a recovery in both precipitation and streamflow.

Increased use of water upstream accounts for a minor part of the lower annual flow of the Columbia from 1900 to the early 1940's. The greater part of the reduction seems related to a climatic differential from the mean.

River basins in the West in 1916 or so entered a period of precipitation far below that of previous years. The period lasted nearly 25 years. Economic losses were serious, and some areas were retarded in growth. Years from now we shall know whether a recent upward trend of precipitation and runoff in many (but not all) western river basins is a temporary or a long-lived recovery. Conversely, a prediction now of an extension or worsening of the 1952–1955 drought in New Mexico and other parts of the Southwest would be of doubtful authority, because predictions heretofore of long-term precipitation cycles have not been worth very much.

In fact, the most valid conclusion we can draw from such studies of precipitation fluctuations seems to be that each succeeding dry year or a sequence of dry years brings us closer to a wet year or a connected series of wet years. But such forecasting does not satisfy the economic needs of the hundreds of thousands of users of water in the West, who are concerned with immediate planning for the best utilization of seasonal water supplies.

Therefore, beginning near the climax of the severe drought of the 1930's, the users of water began to develop the systems of snow surveying as a basis for dependable prediction of the seasonal flow of the western rivers.

SNOW SURVEYS determine accurately and quickly the amount of water accumulated in the mountain snow pack.

A slotted aluminum sample tube, having a circular saw-edge cutter point, is thrust vertically from the snow surface to the earth beneath. After the tube is withdrawn, an earth plug or ground litter in the cutter proves that the entire depth of snow was sampled.

Usually 10 to 15 samples, or enough to provide a dependable average, are taken at each snow course. The points on the courses are separated by measured spacings, usually 50 to 100 feet apart, along a permanently marked and mapped route. The samples are taken at the same locations every year.

The independent snow survey networks of the West were coordinated in about 1935 by the Bureau of Agricultural Engineering. The Bureau was conducting snow surveys for the purpose of forecasting supplies of irrigation water. This activity was later transferred to the Soil Conservation Service. More than 1,200 snow survey courses were in operation in the West in 1955.

The work is done by men trained in mountaineering and in travel of all kinds over snow through the wilderness areas. The men come mostly from ranks of the Forest Service and Soil Conservation Service. In 13 consecutive seasons, up to 1954, they completed their appointed rounds, travelling by ski and snowshoe more than 300,000 miles, without fatality, and obtained about 575,000 samples of snow. The men travel in pairs for safety's sake, because their routes lie through the most rugged terrain in the West.

The use of aircraft has cut the costs of the surveys. The pilots of lightweight, ski-equipped planes land in meadows or in clearings and take samples. Markers of unique design are erected on the snow courses in some places. The snow depth is read directly by pilot or observer in a low-flying aircraft, and the reading is converted to water equivalent of snow. The method is used mainly for the preliminary winter surveys and we do not rely on it widely for the more precise

Measurements of deep snow are made by coupling together sections of the lightweight tubing, calibrated into ½-inch divisions along its entire outer length. Thus the depth of snow can be read after the sampler has been driven to the soil beneath.

results necessary to the final spring forecasts of runoff.

The snow surveys do not attempt to measure the total volume of water stored within a basin. They measure instead the water content of the snow along the related snow courses. The information from a few snow courses in a large drainage basin provides an index to the snow-water accumulation over that watershed. Snow courses at high elevations better reflect the accumulated winter's precipitation than courses at low levels, since little melt-

ing occurs in winter at high elevations. But snow courses at intermediate or low elevations are used to confirm the presence or absence of snow at those levels and provide correction factors to the snow survey data from high elevations. Snow courses at low elevations sometimes are useful as indicators of a potential hazard of floods from snowmelt.

FORECASTS OF WATER SUPPLIES based on snow surveys rest on the fact that measurements of water accumulated in mountain snow at a few locations on the headwaters of a stream are related directly to the streamflow from that watershed.

The forecast in the accompanying chart is for a snow- and rain-fed river, North Fork of Rogue River above Prospect, Oreg. To forecast the seasonal runoff from that watershed, once the water content of the snow cover is known, the measured water content as obtained from the snow survey is located on the water-content (vertical) scale of the graph. A line is projected horizontally from this point to the snow-cover runoff curve, and is there dropped to the runoff (horizontal) scale. Direct reading of the forecast value from the runoff scale thus is possible. The runoff value may require adjustment to allow for other variables in the snow areas, such as the status of watershed soil moisture.

Storage of water on mountains occurs in two main forms. The first and most obvious is the enormous water storage in snow. Appreciable, although usually less important, storage is found below the ground surface, either in the soil mantle or within caverns or interstices of the underlying formations.

Watersheds differ greatly in this respect. Parts of the granitic Sierra Nevada in California have a shallow soil mantle, and the parent material underneath is lacking in voids; relatively little water storage occurs therefore other than in the form of snow. In the lava formations in parts of Oregon and Washington, an immense amount of water is stored beneath the ground surface. That subsurface storage often affects later streamflow. The relationship of snow cover and runoff in any season is influenced by the status of watershed soil moisture at the time of spring snowmelt. Snow on dry soil is less effective in creating streamflow than the same amount of snow on wet soil.

Water stored in soil on a watershed does not of itself contribute to streamflow, because water so held is removed only by evaporation or by plant transpiration. Once watershed soils are filled with water to field capacity, however, additional water added to the surface will find its way to the ground water, later to reappear in streamflow, or will flow directly over the ground surface into collecting channels to contribute at once to surface runoff. So the capacity of watershed soils to store water is important in determining what percentage of the annual snow cover will be required to "prime" a soil before sizable volumes of water can be produced to sustain streamflow.

What percentage of the seasonal snowpack is required to restore the watershed soil moisture deficiency to "normal" in differing watersheds in different years?

You have to have a dependable answer to that question in order to make an acceptable forecast of runoff. In seeking the answer, the Department of Agriculture has installed Colman fiberglass electrode units at different depths in soils of watersheds. Some 50 such pilot installations in watersheds of widely different types are being observed to determine if the equipment and the procedures will give useful and correct answers. In the meantime, forecasts rely on indirect indices to the "soil priming" factor, such as base flow values for rivers during autumn or precipitation values recorded for autumn at gages located mostly in foothills or valleys.

A further problem in forecasting the seasonal runoff is that of climatic departures from the mean during the

runoff season. Cold or warm and wet or dry spring weather affects the rapidity and volume of snowmelt and so affect the accuracy of the forecast. Such climatic departures for 30 to 90 days in advance cannot be foretold yet with dependable accuracy, although progress in long-range weather forecasting has been reported. Snow survey forecasters in the Upper Columbia River Basin have been using the 30-day outlook prognostic of the Weather Bureau to qualify runoff forecasts.

RUNOFF FORECASTS available for consideration and use by managers and water users of the western rivers are of four types:

(1) Forecasts of volume for the annual runoff. These are based largely upon analysis of rainfall records mostly at lower elevations and are issued in monthly publications by the Weather Bureau from January 1 to May 1.

(2) Forecasts of volume for the seasonal runoff. These forecasts for the Western States are based chiefly on snow surveys and partly on related weather data. Forecasts for California are presented in monthly reports of snow surveys, January through May, issued by the California State Division of Water Resources, the agency responsible for snow surveys in California. Forecasts for British Columbia are included in similar bulletins for that Province, issued monthly by the Water Rights Branch of the Department of Lands and Forests, the agency responsible for the snow surveys in British Columbia.

Forecasts for other western river basins are included in the numerous cooperative State-Federal snow survey bulletins, mostly issued monthly by the Department of Agriculture in cooperation with State and private agencies in Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming. The Federal-State-private cooperative snow survey forecasts for the West as a whole encompassed forecasts for 313 river gaging stations in 1954.

The volume forecasts are usually for April–September, but some are for April–July or April–August, and some are for July–September, depending on the most critical period of need for the seasonal flow.

(3) Forecasts of approximate dates of streamflow recession to any given rate of flow. Such forecasts are useful in estimating water supplies to be available for users whose water rights are of low priority. Research on the forecast of actual daily distribution of the volume amount has seemed promising for highly complex commercial operations in which water supplies are critical.

(4) Forecasts of potentially high peaks of flow. These forecasts are useful in advance planning for control of possibly dangerous flood peaks.

THE HIGHEST ACCURACY of forecasts from snow surveys is noted in the watersheds where the greater part of the seasonal runoff derives from snowmelt and the least part of that runoff results from direct rainfall during the seasonal runoff period. In the North Pacific Coastal Drainage, for example, annual accuracy ranges from 80 to 90 percent, with an average of about 86 percent in recent years.

Substantial contributions to streamflow in the Upper Missouri Basin often result from rainfall on the watershed during April and May and after the main forecast is issued on April 1. The average accuracy of the forecasts in this basin is 80 percent. In the Columbia River Basin, where a proportionately lesser part of the seasonal runoff is due to rainfall during the period of seasonal runoff, the average accuracy has been 84 percent.

Entirely accurate forecasts are hardest to make in basins of the Arkansas and Rio Grande Rivers, largely because the departures from the average of precipitation and temperature during the runoff period are wide.

On many individual streams in the West the forecasts are of a fairly high order of accuracy. On Squaw Creek,

one of the smaller streams used for farm irrigation near Bend, Oreg., the minimum accuracy in 12 years of forecasting was 88 percent, the maximum was 100 percent, and the average 94 percent.

Usually the smaller the seasonal flow volume of a stream, the greater the possible error of forecasting, because even one rather heavy and unexpected summer storm can easily double the runoff that was expected for the entire irrigation season.

I believe the seasonal forecasts based on snow surveys will become more and more accurate, as historical records increase in length and as our search for improved forecasting techniques bears fruit. It is unlikely, however, that accuracy much above 88 percent for the whole West can be had until entirely dependable long-range weather forecasts become available.

On a given soil type in a specific area, the water requirements of irrigated crops can be stated precisely. Should too small a seasonal supply of water to serve the usual cropped acreage be forecast, farmers could choose between lower production with higher unit costs on the usual acreage and (preferably) seeding only the acreage for which there will be enough water. Time, seed, crops, and money are saved by such planning. When severe shortages of water are foreseen far enough in advance, some opportunity is given for developing supplemental supplies, usually from ground water.

An example of applying the information from snow surveys was given in 1934, a year of critical water shortage. George D. Clyde, formerly an employee of the Department of Agriculture and later director of the Utah Water and Power Board, wrote about it thus:

"As early as February it was known from midwinter snow surveys that Utah was facing a serious drought. There was an extremely light accumulation of snow on the high watersheds and the soil under the snow was dry, the lower watersheds were completely devoid of snow, and the valleys had experienced only light precipitation. These drought conditions continued unabated until April 1, when the snow surveys clearly indicated that Utah faced the worst drought in her history. At that time the potential water supply did not exceed 35 percent of the normal. These conditions were immediately brought to the attention of the Governor. He called the first drought conference in history to be held before the drought occurred. At this conference two lines of action were developed: First, to put into effect at once a water conservation program, and second, to begin immediately the development of supplementary water supplies so that they might be available by the time the crops needed water. As soon as the water users were convinced that a real shortage of water existed, they began planning and executing a program to combat the drought. They did not wait until the drought was upon them before beginning operations.

"As a result, they matured most of the crops they planted; they saved their orchards and perennial plantings; they moved their livestock off the ranges and out of the State before they starved; and they developed supplementary water supplies for irrigation and culinary purposes before the ordinary sources dried up or became so low as to be unable to meet the minimum demands.

"The water development program enabled the State to develop about 400,000 acre-feet of water to forestall crop failures. Estimates based on measurements made during the season of 1934 indicate the saving in crops alone was over $5 million in Utah.

"The water supply forecasts enabled municipalities to early inaugurate a water conservation and supplementary development program which gave them sufficient water in most instances to carry them through the drought. It

enabled power companies to provide supplemental steam power in advance of its needs. Early warning enabled Salt Lake City to develop a supplemental water supply of 40 to 50 second-feet from ground water. These latter benefits cannot be evaluated in dollars and cents, but they rank high in prevention of human suffering and economic loss. The experience of Utah in 1934 was duplicated that year in many of the other Western States."

In years of abundant snowfall, emphasis in the forecasts may be placed on the abundance of water to be expected, rather than on any possible shortages. Crops that need a great deal of water can be sown, or increased acreage can be brought into production. As a further result, many water-storage reservoirs may be used as flood-control structures to regulate streamflow to reduce flood crests and yet insure safe and maximum storage contents for later irrigation.

In 1950, following snow survey reports of unusually heavy snow packs on tributaries of the Columbia River, action taken by Federal and private agencies along that river were responsible for the following report, which appeared in the October 1950 issue of Reclamation Era:

"Thirteen Reclamation reservoirs saved $5,600,000 in flood damages during the June 18 through July 15 flood crest on the Columbia River and its tributaries. This estimate of the potential damages which were averted by control of floodwaters at Reclamation reservoirs does not include damages averted by levees, for which figures were not available at the time."

Snow surveys are proving of value to flood control and levee districts and to some industrial plants on the streams where high flood flows may occur from melting snow, because the advance warning allows preparations to guard against loss of crops.

Data from snow surveys provided the basis for a forecast of a potential flood which would affect the Bonners Ferry locality in Idaho. The forecast was issued April 9, 1954. A second forecast on May 10, 1954, contained a specific prediction that a 35.5-foot river crest could be expected at Bonners Ferry at the time of the spring snowmelt rise of the Kootenai River. With such warning, Federal troops and heavy equipment were rushed to Bonners Ferry.

The town was largely evacuated. The dikes were reinforced. The river reached a peak at 35.55 on May 21, 1954. Only about 6,000 acres of good farms were flooded as a result of dike failure. The town was spared.

R. A. Work *became head of the Snow Survey and Water Supply Forecasting Section of the Soil Conservation Service in 1953. He has been directly concerned with runoff forecasting since inception of the Department's snow survey program in 1935. He was graduated from the University of California in 1927, and joined the Department of Agriculture in 1929.*

Soil and water are the very foundation of our agriculture and of our whole Nation. It is therefore the responsibility of every American — every individual and every group — to work together to see that these resources are used wisely and protected for the use of generations that will follow.

—Clinton P. Anderson

In addition to the flood prevention or control we are likely to think of first when considering watershed problems, there is another problem, and one of particular interest in this part of the country. Someone has termed it "drought control." The watershed job doesn't consist solely of holding back stormwaters and keeping them from doing damage to the land and property. Making the fullest use of water always has been an important part of soil and water conservation. An important part of the watershed job accordingly is to provide for making beneficial use of the water on the land close to where it falls.

—D. A. Williams

Fog, Mist, Dew, and Other Sources of Water

F. W. Went

The main sources of water for crops in most agricultural areas are rain or irrigation. In many parts of the world, however, neither rain nor ground water seems to be enough to account for the development of the naturally occurring vegetation. In those places we have to look for other sources of water—fog, mist, and dew—and their possible contribution to plant growth.

On many days and in many localities, plants are covered with dew in the early morning. Because dew disappears soon after sunrise, people often overlooked it as a possible source of water, which they consider to be most necessary in midday. The question, however, is not whether water droplets stay on the leaves for a long time but whether the water can contribute in any way to the growth of plants. In other words, does enough of the dew water reach the soil or is a sufficient amount absorbed by the plant itself to improve the whole water supply?

The question has been investigated by S. Duvdevani, who compared two field plots of plants that were treated identically except for the possibility of dew formation at night. By placing a canopy over one plot between sunset and sunrise, he prevented formation of dew on the plot without interfering with the temperature or the movement of air over the plants. He conducted the experiments in the coastal plain of Israel, where dew occurs frequently and sometimes is rather heavy. The tests showed that most plants, such as squash and corn, grew about twice as much when they received dew during the night. Therefore it would seem that in a semiarid area, dew has considerable importance in the growth of plants. Three possible reasons come to mind.

In the first place, the dew water could run off the leaves and collect in the soil on which it drips. The amount of dew, however, is too small to wet more than a few millimeters of the soil.

In the second place, it is possible that the dew water is absorbed by the leaf surface, on which it condenses, and thus is used directly by the plant. That was found to be the case; young leaves especially can absorb the dew as rapidly as it forms. One can often observe that after a night of heavy dew the young leaves of shrubs and herbs are quite dry and the older ones are covered with dew. This absorbed water can be moved to other parts of the plant and can even be excreted by the roots into the soil. Such water would be available again the next day. It was actually found that the soil around root systems of plants is more moist when they are subjected to dew than around roots of plants that do not receive dew, despite the fact that the dew-covered plants are larger and must take more water from the soil.

In the third place, water saturation of a plant is essential for its growth. As growth in most plants occurs during night, a water supply would be most effective at night. These observations therefore make it very likely that dew can contribute to the better development of plants, at least in semiarid regions.

Experiments with the yellow pine by E. C. Stone and H. A. Fowells have shown that when yellow pines are grown in very dry soil, which is unable to supply water to plants like sunflower, they will survive for a limited number of weeks (on the average, 3); however, when such plants are sprayed every night with a fine mist simulating dew, they can survive for 7 weeks without any further water supply through their roots. That is another indication of the possible importance of dew in the life of plants.

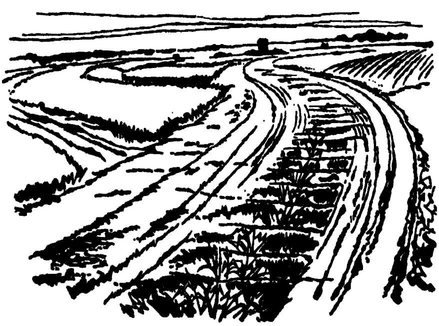
Field observations also tend to indicate that there must be another source of water for plants in semiarid regions where rainfall is insufficient for normal

growth of plants. As an example, the growth of a number of annual plants during the dry season in southern California can be mentioned. Some plants, among them the wild buckwheat (*Eriogonum fasciculatum*), some gilias, and *Stephanomeria*, manage to continue development many months after they have received the last rain.

If they had an extensive root system, they might be able to extract enough water from the drying soil, but these plants and others have only restricted root systems and few active rootlets. They certainly must have exhausted in a short time the small amount of soil with which they are in contact. When such plants still manage to keep green and even grow, it means that there must be another source of water than what is stored in the soil around their small root system. Because their water requirement cannot be satisfied from below, it must come as atmospheric condensation.

Is dew a frequent enough phenomenon and is it of sufficient intensity to account for its apparent role in plant growth as demonstrated in the examples I mentioned?

To get an answer to that question, many investigators have devised methods to measure dew under natural conditions. They have used various gages. The one most extensively used and accepted is that of Dr. Duvdevani. It is a wooden block with a standardized painted surface, which is exposed to dew at night and on which the occurrence and quantity of dew can be read



in the morning according to the pattern of dew droplets deposited. The heavier the dew, the more the droplets have coalesced. By comparing the dew patterns with photographs, one can standardize the observations. With the gages Dr. Duvdevani studied the distribution of dew in Israel and found four interesting relationships.

First, the amount of dew is higher in the dry summers than in the wet winters.

Second, even in the dry and hot Jordan Valley dew is a common phenomenon and occurs on nearly half the nights. In the Southern Desert (Negev) it is even more frequent.

Third, considerable differences exist in dew deposition according to the topography of the land.

Fourth, deposition of dew in summer increases with distance from the ground, but in winter the opposite dew gradient is found—proof that the water deposited as dew did not originate from the ground but was of atmospheric origin. The total amount of dew precipitation in Israel amounted to approximately 1 inch a year.

Other investigators found a similar figure in other parts of the world and therefore concluded generally that dew could not account for more than 1.5 inches of precipitation. That amount undoubtedly is too small to explain the considerable increase in growth that observers have attributed to dew.

Instead of measuring dew deposition with gages, we can also calculate how much dew could be produced theoretically. Dew is produced when leaf and other surfaces are cooled to a temperature below the dewpoint of the air. This cooling is accomplished by radiation of heat toward the sky.

A large amount of heat is radiated by the sun during the day. The radiation amounts to approximately 1.2 calories per square centimeter a minute. It is transformed partly into long wavelengths and partly into heat of evaporation.

Some of the radiation heats the soil.

Because, on the average, the earth does not become warmer, all radiation absorbed by the ground has to be reradiated by the ground at night in the form of long-wave heat radiation. That radiation is partly absorbed by water vapor in the atmosphere. The drier the atmosphere, therefore, the greater the amount of outgoing heat radiation and the stronger the cooling of the surface will be. On clear nights this radiation amounts to 0.16 calorie per square centimeter a minute at a relative humidity of 100 percent; 0.20 at 40 percent; and 0.25 at 15 percent. As leaves and other surfaces lose heat through the radiation, they are cooled and ultimately may reach the dewpoint of the air. As soon as that happens, dew is deposited and no further drop occurs in the temperature of the leaves.

FROM THE AMOUNT of heat exchange we can calculate the amount of dew that can be deposited. At a relative humidity of 40 percent, it takes about 500 calories to lower a sufficient air volume to the dewpoint to deposit a gram of water, which also required about 570 calories of heat of condensation. About half of the radiation, or 0.1 calorie per square centimeter a minute, is therefore available during clear nights for dew deposition. For a whole night that amounts to 1 millimeter of dew. For a whole year of 365 cloudless nights it is equivalent to 15 inches of rain. That amount is rather independent of the relative humidity of the air, because in dry regions the radiation is greater but the amount of dew deposited per calorie is less, whereas in most climates the radiation is less, but it is more effective in producing dew.

These 15 inches of potential condensation from the air is in sharp contrast to the 1.5 inches measured with dew gages. We should try to find the actual amounts of dew that are deposited on a natural cover of vegetation. That has been done in several ways. In the first place, we have a set of measurements by C. W. Thornthwaite and Benjamin Holzman, who measured the water vapor gradient from soil toward the air. By taking into account the rate of air movement, they could calculate how much water vapor was lost or condensed on the basis of this water vapor gradient, and they calculated that a total of 1.81 inches was condensed on a meadow surface for a 10-month period in 1939 in Arlington, Va. During that time, a total of 26.3 inches was received in the form of rain and snow, which would indicate that not more than 7 percent of the total water supply to this meadow had come in the form of dew.

By actual weighings of an area of soil covered with grass, corn, wheat, or other crop plants, the amount of nightly condensation can be measured.

That was done in lysimeter experiments at Coshocton, Ohio, by L. L. Harrold and F. R. Dreibelbis. Hourly weighings would indicate the increase or decrease in weight of the blocks of soil. Their increase in weight was due to rain or to dew, but they lost weight through transpiration and evaporation.

In a series of measurements over a 6-year period, it was found that an average equivalent of 9.1 inches of rain was deposited throughout the year in the form of dew—approximately 20 percent of the total water supply came in the form of dew. When we compare this figure with the 15 inches that could theoretically be deposited during 1 year of clear nights, we find that the actual observations agree quite closely with the measured condensation in the lysimeters. We have to take into consideration that on many cloudy nights dew cannot be formed.

CALCULATIONS and actual observations apparently agree that dew is a potentially important source of water for plants. As it may amount to about 10 inches of precipitation a year—in line with field experiments such as those of Duvdevani—more work should be carried out to establish the exact conditions under which the greatest amount of dew can be deposited.

As I mentioned earlier, dew can be deposited only when the sky is clear. There is no dew on cloudy nights; semiarid regions therefore are more favorable for dew deposition than most other climates. Not only do clouds prevent the nightly radiation toward the sky; dust and haze also will prevent it. Dusty areas, such as the Sahara, and regions with much haze, like the Los Angeles area, therefore, have very much less dew than areas with clear night skies, such as the southwestern desert areas and Israel.

Considerable differences in the formation of dew can be expected according to the nature of the terrain and velocity of air movement past the condensing surfaces. In completely still air, only the amount of water vapor that can diffuse toward the leaves will be condensed, and that amounts to less than 1 percent of the greatest possible dew deposition. When, on the other hand, strong winds move the air too fast past the leaves, their temperature will not reach the dewpoint, and therefore no dew will be deposited at all. Optimal dew formation can be expected when an intermediate amount of air comes in contact with the leaves.

In the future we should investigate all conditions that affect dew deposition so that it might be possible to increase the effectiveness of dew and increase the amount condensed. It is quite possible, for instance, that by the judicious spacing of trees and shrubs through natural air drainage the optimal amount of air movement can be achieved so that the greatest possible amount of dew will be formed.

Dew seems to be particularly effective in a number of coastal areas around the world. In several such places that have too little rainfall, very heavy dew apparently can carry the crops to maturity without the help of irrigation.

An example is the coast of southern California. Immediately adjoining the ocean is a zone one-half to a few miles wide where tomatoes, peppers, beans, and other vegetables can be grown in summer. Those crops develop well even without irrigation, although no rain falls during the growing season from May to October. The soil in the region may contain enough moisture for the first few months of growth but definitely not enough for the last few months. If growth and production are good nevertheless, that means there must be some other source of moisture. The source can hardly be anything else but dew or coastal fog.

Fogs and mists are really low-hanging clouds in which the water droplets are so small that they do not settle on horizontal surfaces and thus do not register in a rain gage. Consequently they usually are not considered important as sources of water. Yet fogs may be important to plants.

Vegetation in many places where fogs are frequent differs from the vegetation in nearby localities where fogs do not occur. One of the best examples of this is the northern coast of California. Redwoods occur there predominantly in a narrow belt and never range inland beyond the influence of sea fogs. In places where more water is available, redwoods grow very well outside the fog belt—an indication that fog is important in their water economy. In this belt, fogs occur almost daily. Anyone who walks in a redwood forest during a fog finds that the trees are dripping, although in nonforested spots nearby not a drop falls. That means that the redwoods are able to condense the fog droplets to larger drops.

This same dripping of trees in fog one can observe in pine forests in the mountains or under live oaks in the California foothills during autumn fogs. In the latter instance it can be seen that this fog-drip water is effective for the vegetation. Rain would wet equally the ground under and around the trees and therefore would not account for the greener color of the grass or the extensive germination of wild plants under the trees. But during fogs,

water drips under the trees and actually moistens the soil within the perimeter of their crowns. If it were merely shade that enables the seedlings to become started or encourages the growth of grass, the green area would extend north beyond the tree. That it does not do.

LET US QUESTION for a moment how trees can condense moisture from fogs. A fog consists of very small (0.01–0.1 millimeter) water droplets, which are far enough apart that they do not fuse, are suspended in saturated air so that they do not evaporate, and are light enough not to settle. Furthermore in a fog there is usually enough air movement to stir up droplets about to settle. When such a fog moves past solid surfaces, it is deflected, and the water droplets flow with the air around the surface and prevent contact with it. If the surface is small or narrow enough, the air is hardly deflected, and the inertia of the water droplets is sufficient to carry them against the surface, where they fuse with it. That means that small or narrow surfaces will act as strainers for the fog droplets. It is an interesting fact that the diameter of pine or redwood needles is such that they condense fog droplets very efficiently at the normal rate of fog movement. That can best be seen in hoarfrost or rime, which develops when a fog touches surfaces, where the condensed fog droplets freeze immediately upon contact if the temperature is below freezing. Under such conditions a ribbon of ice extends from telephone and other wires in the direction from which the wind came. But we also see that hoarfrost covers all pine needles, although the larger leaves of broad-leaved trees have hoarfrost only along their edges and not over their surfaces. That shows how much more effective the needle form is for condensing fog droplets.

We can now return to the effectiveness of fog as a source of water in nature. Stagnant mists cannot serve as a source of water because the condensation occurs only when a sufficient volume of air with fog droplets is carried over the condensing surface. Therefore the ground mist developed through rapid cooling at night of the air nearest the soil is ineffective for condensation of the fog particles. But coastal fogs formed by moisture-laden air rising against coastal ranges, or clouds forming against the mountain ranges by lateral air movement which forces air up against the mountain slopes, are ideal for fog condensation.

In regions where such fogs occur rather regularly, a tree or shrub vegetation grows that is rich beyond what the actual precipitation records would make one expect. Along the California coast, the redwood growth is phenomenal against the western slopes, but against the eastern slopes, with approximately equal amounts of rain, tree growth is much poorer. The difference indicates the degree to which water precipitation from fogs is effective.

In the drier areas in the West, there are series of high mountain ranges in areas with insufficient precipitation for tree growth. On the mountains we find a lower timberline, below which trees do not grow. If the timberline were due to reaching the threshold value of precipitation where tree growth was barely possible, one would expect a ragged and irregular timberline, with the trees gradually thinning out.

But along the eastern slopes of the Sierra Nevada, for example, one sees a sharp horizontal line of demarcation, below which no trees occur and above which a normal pine forest is found. The line coincides with the level at which clouds are formed by eastern winds.

IN MANY DRY REGIONS, such as the areas covered with chaparral in California, many of the most characteristic plants, such as chamise (*Adenostoma fasciculatum*) or wild buckwheat (*Eriogonum fasciculatum*) have developed very small leaf surfaces in the form of

needlelike leaves. They are not an adaptation to reduce transpiration, as is often suggested, but probably are effective in condensing water from the occasional fogs.

In dry regions bordering a coast, we may find so-called fog deserts, areas with very little precipitation but with frequent fogs. Typical of such areas are southwestern Africa and the coast of Peru. In both, mountains rise immediately behind the coast and cause the formation of fog as the air rises against them. In each, also, a cold ocean current (the Benguela and the Humboldt Currents) limits the total amount of moisture present in the air, so that the total precipitation is about 1 inch a year. The lowlands near the coast, where no fog occurs, are practically without vegetation, but at 1,000 feet a shrub vegetation beyond expectation occurs where fogs hang most of the year. Indicating the high humidity during most of the day is the richness of the epiphyte vegetation. Even on cacti, like *Trichocereus*, grow many lichens and several tillandsias, which ordinarily are found in moist rain forests. And on the trees (*Caesalpinia* and *Zizyphus*) mosses and peperomias cover the branches, which consequently seem several times thicker than they are.

The importance of the actual condensation of fog droplets in fog areas can be seem in several places. Just north of San Diego there is a small area where the Torrey pine occurs. The trees are limited to the upper parts of the slopes facing the ocean—that is, where the fog comes in closest contact with the vegetation. On the lower parts of the slopes and a few hundred feet inland, the pines disappear. It is an otherwise very dry area, as indicated by the much poorer shrub vegetation anywhere except on the ridges bordering the ocean. A similar phenomenon can be observed along the Mediterranean coast. Just behind Oran in Algeria rises a plateau with a rainfall of about 15 inches—enough for some pines but not enough for the holly oak (*Quercus ilex*). However, this oak is found only along a strip 10 feet wide that follows the ridge of the tableland, again the place where fog will hit most and where (through droplet condensation) the water supply is more abundant.

One can get an idea of the total amount of liquid that can be precipitated by such fogs by using a rain gage, over which a set of fine wires or branches is placed. The wires or the branches will condense the fog droplets, which then drip into the rain gage. Such an arrangement disclosed that during a particularly heavy storm, when clouds were swept over the Table Mountain in South Africa, only 0.2 inch of precipitation fell in a regular rain meter, but in a similar rain gage, in which branches had been placed, 6 inches of precipitation was collected. It seems a worthwhile project to investigate this fog condensation in greater detail.

The relative humidity of the air may be important in the conservation of water by plants. Under otherwise identical conditions, water loss by transpiration will be proportional to the saturation deficit of the air. As the saturation deficit increases beyond a certain point, however, phenomena (such as incipient drying) stop a further increase in transpiration. Plants that themselves have a saturation deficit will lose water toward the atmosphere only if the saturation deficit of the air is greater than that of the plants. At a diffusion pressure deficit, or suction force, of 100 atmospheres, such as can be found in arid regions, plants will be in equilibrium with air having a relative humidity of 93 percent. That is to say that they will lose water by transpiration only when the air is drier than 93-percent relative humidity but will take up water vapor from the air when this is more moist than 93 percent. In a number of experiments, E. C. Stone, C. L. Young, and I found that several chaparral plants can take up water vapor from air with a relative humidity of 85 percent or more.

Therefore we should consider the possibility that absorption of water vapor can be a source of water for certain plants. This I found to be true of several tropical orchids, which hang from the branches of jungle trees and obtain liquid water only during actual rainstorms. When the relative humidity in the forest was 95 percent or more, the orchids took up water vapor and increased in weight. Since the relative humidity inside such forests remains above 95 percent more than 12 hours a day, water vapor was a significant source of water for the plants.

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Conversion of Saline Waters

David S. Jenkins, R. J. McNiesh, and Sidney Gottley

Reclaiming water from otherwise unusable sources, by removing dissolved salts from saline water, is coming to be regarded as a probable way to supplement our traditional water supplies.

The process is known as conversion or the demineralization of saline or sea water. One of the sources is the relatively static and indispensable water of the oceans, which contain most of the world's water. Its use would supplement the short supplies along coastal areas. Another source is the brackish water now found inland—much of which is becoming increasingly saline to a point where it can no longer be used for some purposes without harmful effects.

In either case, the salts held tenaciously in solution must be removed before the water becomes suitable for agriculture, industry, or domestic use.

Although sand, sediment, and other foreign particles can be removed simply by filtration, salt cannot be removed so easily.

Saline water is a relatively simple system of inorganic salts dissolved in water. It has certain physical and chemical properties that determine the various methods by which the salts may be separated from the water. The system, although not complex, is comparatively stable; because of the stability, separation of saline solutions requires relatively large quantities of energy.

Theoretical calculations show that at least 2.8 kilowatt-hours (3.8 horsepower-hours) of electrical energy is required to separate 1,000 gallons of pure water from sea water. Thus, more than 900 kilowatt-hours (more than 1,200 horsepower-hours) must be used to obtain 1 acre-foot of fresh water from sea

water. If electric power costs 1 cent a kilowatt-hour, the cost of theoretical separation is 2.8 cents for 1,000 gallons or more than 9 dollars for 1 acre-foot of fresh water from sea water. The figures are independent of the type of separation process and represent only the energy necessary to separate pure water from an infinitely large body of sea water.

Those figures represent complete theoretical perfection—something neither man nor his machines can achieve. The minimum costs must be expected to multiply several times in translating them into practice. Just how many times is not known—or may never be known—but continued research should bring improvement of processes and a consequent reduction in costs.

Studies undertaken by the United States Department of the Interior, through a contract with Dr. George W. Murphy and his associates of the Research Foundation of the State University of New York, show what practical minimum energy rates are attainable for less-than-ideal conditions. For compression distillation and electric membrane processes, a minimum of about 12 killowatt-hours for 1,000 gallons was found. That is about four times the absolute minimum attainable under ideal conditions. Of course, it is still theoretically possible that other methods now under investigation, or yet to be devised, could operate with a lower practical minimum.

The question then comes up as to whether we must abandon the possibility of extracting fresh water from sea water at costs attractive for general consumption, such as irrigation. The answer is, of course, no. What is theoretically possible is still a challenge to man's ingenuity. Besides, vast sources of energy are available to us, like sunlight, the thermal difference between surface water and subsurface water in the oceans, windpower, and geothermal energy; any of them may be essentially free to us if effectively harnessed.

In addition to the energy cost, the capital investment and the operation charges determine the total economy of any process. All three must be included, although all too often investment cost is either omitted from calculations or is inadequately treated. Processes by which fresh water can be produced from sea water, at a total cost competitive with the other sources of water in the continental United States, have not yet been developed, but continuing research and development work in this field are bringing us closer and closer to such a reality. In fact, there are now many installations over the world where salt water is being converted to fresh in substantial quantities, permitting the profitable functioning of industries which, without such conversion, probably could not exist.

It has been suggested frequently that the yield of marketable byproducts by separation processes might provide revenue to offset other costs for the production of fresh water in large quantities. Although large-scale conversion of saline water could supply large tonnages of many elements, the byproduct credit per unit of water processed would probably be insufficient to make conventional conversion systems economically suitable for general use, such as irrigation. Coupling byproduct credit with new demineralization processes offers considerably more promise. If processes can be developed by which several minerals can be extracted at one time, their value in some market areas might be such as to reduce the cost of the water by that small amount necessary to attain economic feasibility.

Suggestions that the atomic energy might be used in some way in demineralizing saline water have been analyzed, and the following conclusions have been reached, in cooperation with representatives of the Atomic Energy Commission: (1) Direct use of nuclear fission for separation of salt from water cannot be foreseen at this time; (2) Direct heat from reactor plants could be used in the various demineralization processes. However,

such heat must be less costly than other forms of heat, and there appears to be some possibility of its use for this purpose.

Future developments in the use of nuclear energy and improvements in demineralization processes could hasten this use of this heat substantially. Low-cost energy plus new demineralization processes may provide one answer.

SEVERAL METHODS are in general use for demineralizing highly saline waters on a substantial scale. Three involve evaporation of some of the saline water and the condensation of the resulting vapor. Each employs some means of economizing on the fuel that is burned to generate steam. The processes are termed multiple-effect evaporation, flash evaporation, and the vapor-compression distillation.

Multiple-effect evaporation is the method most commonly used on board ship for refining sea water and is also the only method that has been employed for large, permanent, shore installations. Steam is generated in a fuel-fired boiler or evaporator. The vapor produced in this first-effect evaporator is condensed in the heating coils of an adjacent or second-effect evaporator, operating at a slightly lower pressure, thus furnishing heat for evaporating more sea water. By employing several (up to 6 or 7) such evaporators in series, the amount of heat that is ultimately wasted as cooling water in the last condenser is decreased as the number of effects is increased. The resulting fuel economy is achieved partly at the expense of increased installation costs.

A second process employs flash evaporation, wherein water at a particular pressure and temperature is released into a chamber of slightly lower pressure, where the liquid flashes into vapor and is subsequently condensed. This principle has been applied to the production of potable water from sea water in several stages at subatmospheric pressures. The process has been found to have advantages in reducing the weight and space requirements of shipboard sea-water distilling plants and in reducing the formation of scale in such plants. In comparison with submerged-tube evaporators, where heat-transfer coefficient is a function of temperature difference, this type of plant has no comparable losses in heat-transfer coefficients with reduced temperature difference per stage and no losses of temperature difference due to hydrostatic head. The optimum number of stages therefore is usually greater than the optimum number of effects in a submerged-tube plant, and the corresponding fuel consumption is less.

Vapor-compression distillation is a third method in current use. Portable units of this type were used by military forces for supplying purified water to land-based troops. Such equipment has also made possible some coastal oil developments where fresh water is virtually nonexistent. Energy economy is increased in the evaporative process by recompressing the vapor produced in the unit and condensing this vapor in the heating section of the evaporator itself, thereby producing more steam. The major portion of energy required is thus consumed in driving the compressor, with relatively little additional energy being supplied to generate steam in the evaporator.

Another process now employed has some advantages for certain applications but is quite costly for large-scale, general use. This process operates on the ion-exchange principle and usually incorporates resins, which substitute one kind of ion for another in the water. By a process of regeneration, the resins can be used repeatedly. This type of process is particularly well adapted for water softening and is used most commonly for that purpose. Since chemical compounds exhibit varying degrees of ionization and ionic size, different ion-exchange resins vary in function. Particular resins are designed for specific groups of tasks and new resins are continually being prepared and evaluated to extend their possible

use to demineralizing waters of varying composition. Present costs for converting sea water to a potable liquid by these methods prohibit general and large-scale use.

Present minimum costs of obtaining fresh water from either brackish or sea water by the conventional methods described above exceed 3 dollars for 1,000 gallons. It has been estimated that a reduction to about half that cost is possible by enlarging and improving vapor-compression, multiple-effect evaporation, or flash-evaporation apparatus.

The estimated ultimate cost of demineralized water by conventional systems of evaporation and distillation is more than 10 times the highest prevailing charges for undistributed irrigation water in the United States. It is about 4 times the cost of municipal water in 400 American cities. Presumably, only a relatively few industries can afford these costs for their water supply. Whether or not domestic consumers could afford such prices is tantamount to asking if people would buy food at quadrupled prices. They will if they must, but not if there is any way to avoid it.

It is clear, then, that methods and devices now in use for removing salt from saline water are too costly to be of general benefit for industrial, municipal, and irrigation consumption. In many circles, efforts are continuing to improve the performance of orthodox equipment, particularly by the Department of Defense for military use. However, for the latter applications, mobility, simplicity of operation, and sheer necessity must frequently take precedence over costs for manufacturing and operating. Even rather drastic redesign of equipment used for conventional processes offers little promise of sufficiently reducing costs of demineralizing water to interest the general public.

Because of the constantly expanding need for fresh water and the increase in salinity of many waters already being used in the country, the Congress in July 1952 authorized the Federal Government to participate in research and development in this field for an initial period of 5 years. It provided that the Department of the Interior find practical means for the economical production, from sea or other saline water, of water suitable for agricultural, industrial, municipal, and other beneficial consumptive uses (66 Stat. 328, 482 U. S. C. Sec. 1951).

Under this authorization, the Department of the Interior, through the saline water conversion program, is devoting its efforts to improving the many inland saline surface and underground waters and to converting sea water to useful purposes. This is done by conducting research and development under contract with outside organizations, by exchange of information, and by coordinating private and public research.

Discussion of research efforts in this article reflects their status as of the beginning of 1955.

The scientific research program that is supported by the Department of the Interior is continuously coordinated with the Department of Defense and the National Science Foundation.

Cooperation also exists between the Department of the Interior and the Atomic Energy Commission, the Smithsonian Institution, the Federal Civil Defense Administration, the Department of Agriculture, the Department of State, the Foreign Operations Administration, and the Department of Commerce.

Early studies under the saline water conversion program made it clear that no one process would be likely to meet all the requirements for demineralized water. Indeed, several different processes are needed, each providing an optimum performance under different combinations of location, quality of the existing saline waters, and the character and magnitude of the water demands. Varying conditions that might make one process more desirable than another are:

Salinity of the original water (sea water or brackish water), magnitude and types of industrial needs, extent and size of each municipal need, irrigation requirements of various soils, climates, availability of other water supplies for total or partial blending with totally or partly treated waters, and many other factors that vary from place to place.

For those reasons and because the cost of existing treatment processes so far exceeds the maximum cost considered practicable for many uses, all processes and energy sources that might conceivably be developed into a worthwhile process, must be considered. Clearly impractical processes are being eliminated; others are being investigated and developed. In addition to the extensive efforts being made to improve performance characteristics of the conventional equipment now in use, numerous rather new concepts are being studied.

One process for one major purpose—that of improving brackish water to render it useful for irrigation—is now being tested to determine the durability of operating components and other operating characteristics and to obtain firmer estimates of the overall cost of large-scale water treatment by this means. The Department of the Interior has been investigating the process variables of an ion-transfer membrane demineralizer through a contract with Ionics, Inc., of Cambridge, Mass. This process uses a combination of plastic, perm-selective membranes and electrolysis to remove the salt from salt water. Tests thus far indicate that, since power consumption increases rapidly with the quantity of salts removed, such a unit appears to be most valuable for converting brackish water rather than sea water; the former contains only a fraction of the salts in the latter.

Through a contract with the Badger Manufacturing Co., the Department of the Interior is developing a process conceived by Dr. K. C. D. Hickman, which is a variation of vapor-compression distillation. This new process involves conditioning of the water mechanically to encourage rapid boiling by overcoming a possible obstructive "skin" on the surface of the water. By this means the heat-transfer coefficients are being increased 5 to 10 times those now obtainable by conventional equipment. The cost of distilling water by this method should thus be a fraction of present costs by conventional methods. Initial tests on a laboratory-size unit fairly well confirm the theoretical expectations of the device. Although units incorporating this principle are not now commercially available, no doubt they will be manufactured before long—when further tests prove their possibilities.

Utilization of phenomena at critical pressures and temperature provides another potential separation process. At very high pressure and temperatures, in the order of 3,000 pounds per square inch and 700° F., water reaches a critical condition in which there is no distinction between the gaseous and liquid states. Salt solutions differ from pure water in that saline water retains both the liquid and vapor phases above the critical point of pure water. The higher concentration of salt remains with the liquid phase and, at increasing temperatures and pressures, a larger and larger proportion of the salt collects in the liquid phase. These pecularities of water are essential to this method of demineralization. They permit recovery of process heat for reuse by means of simple heat exchangers because, by maintaining the pressure above the critical point, little or no latent heat of evaporation need be added during the cycle.

Under a contract between the Department of the Interior and Nuclear Development Associates, Inc., suitable conditions for the extraction of fresh water from sea water in this supercritical state are being studied. Work thus far indicates that such extraction of fresh water from sea water is theoretically feasible, although some technical difficulties are recognized. Means of

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overcoming the technical difficulties are not now considered insurmountable.

Still another process in this category is termed "the low-temperature difference method." It is a process in which distillation is achieved, not by heating, but by cooling. That may be accomplished through existing temperature differences, such as those between waste cooling water from existing industrial plants and the sea and rivers into which this water is discharged. Other differences are those encountered between the warm surface water of the ocean and the cooler water at a greater depth in the ocean. The most recent work on a plan utilizing the temperature differences in the ocean has been conducted under French auspices with a proposed plant at Abidjan in French West Africa. Work along this same line is continuing at the University of California, where it is hoped to obtain valuable information, which, added to that gained by the French experiment, will indicate some of the technical problems involved in plants of the large size required.

Two other processes of related nature involve the use of superheated steam or combustion of natural gaseous fuels under water. Both need considerable research and exploratory work before their practicability can possibly be demonstrated.

The use of solar energy for evaporation also involves vaporization in one form or another. Possible application of solar energy, particularly in arid regions where solar intensities are high, usually creates considerable public interest—primarily because the energy consumed is considered free and inexhaustible. Consideration of other cost factors makes the economics of this system somewhat less attractive than would be apparent at first glance. Although the energy may be free, the capital investment is substantial. Presently conceived designs, however, indicate such a system may be better than competitive with conventional processes such as vapor compression distillation and multiple-effect evaporation.

Several studies, including those by Dean Everett D. Howe, University of California; Dr. George O. G. Löf, of Denver, Colo.; the Bjorksten Research Laboratories, Madison, Wis.; Battelle Memorial Institute, Columbus, Ohio (the last three under Department of the Interior contracts), indicate that future improvements in simple solar distillation units and improvement in evaporation plant load factor stand a good chance of reducing production costs to a level where such units would be very attractive in some particular locations.

Crystallization, another physical separation process, involves the formation of a solid crystalline phase from a liquid solution. It is well known as an industrial separation process; the condensation of fruit juices is a familiar one. The formation of ice crystals also is commonly known. Applied to saline water, the procedure would consist of crystallizing either salts or pure water from the solution. It has been found that partial freezing and remelting of salt water tends to separate salt components from pure water.

To understand better the phenomena occurring during the formation of ice crystals in saline water and to discover possible methods of excluding the salts from the pure water upon melting, a contract has been entered into between the Department of the Interior and Applied Science Laboratories, Inc., for some basic research. The apparent advantage of a freezing process over a vaporization process lies in the fact that the latent heat of crystallization of water is about one-seventh that of vaporization. It appears entirely possible that a low-cost process for demineralization by crystallization through refrigeration might be developed.

Sublimation, involving the transition from solid to gas, and vice versa, offers still another opportunity. It depends on the existence of a definite vapor pressure for each different solid. The

vapor pressure for such a material as salt in a water solution might be increased enough at very high temperatures so that a mechanism for separation might be achieved.

Changes in molecular structure and other properties can be induced by a sufficient acceleration of the molecules of a substance. An illustration is the use of vibratory motion of high frequency as a means of keeping materials in suspension. Vibratory motion of frequencies exceeding the limit of hearing (ultrasonics) may be applicable directly to the separation of salts from water or as a means of accelerating or facilitating separation by other processes.

The Department of the Interior has studies progressing at the University of Florida under a contract to determine the physical possibilities of using ultrasonic vibrations in the demineralization of saline water. The research is of an exploratory nature on a laboratory scale.

An important property of solutions is that of osmosis—the spontaneous flow from a more dilute to a more concentrated solution through a permeable membrane. The flow can be prevented by a certain pressure, known as the osmotic pressure, exerted on the more concentrated solution, or it can be reversed by a higher pressure.

Two possible solutions to the demineralization problem, utilizing osmosis, are being studied under the Saline Water Conversion Program of the Department of the Interior. In both instances it is the reverse flow that is of interest, and the membranes are designed to pass pure water only, while repelling ionized material.

One scheme being devised by Dr. Gerald L. Hassler at the University of California involves selective action of an osmotic oil membrane, using the same principle by which body organs and individual cells are believed able to separate fluid constituents. The membrane would be an extremely thin oil layer, which would be supported by capillary action. Water molecules would diffuse through it, while other molecules would be blocked.

Another method is being investigated at the University of Florida, where the possibilities of various synthetic membranes are being tested. Here it has been found that with one such membrane at least 90 percent of the salts can be removed in one pass under pressure. The quantities of demineralized water that can be thus produced are very small, but further work may demonstrate considerable improvement.

The separation of salts from saline water based on their differential solubility in liquids immiscible with water provides another possibility.

It is theoretically possible to add enough organic solvent to sea water to dissolve part of the total water, thereby concentrating the salts in the remaining brine and subsequently separate the water from the organic solvent. Identification of a suitable solvent with the proper affinity for water is the principal task. Separation and recovery problems for both water and solvent should not be insurmountable. Under a contract with the Department of the Interior, the Agricultural and Mechanical College of Texas is conducting exploratory research on the application of this process to the economical demineralization of saline water.

Other physical processes and phenomena might assist in the conversion of saline water to fresh. Among them are adsorption, the retention on solid surface of a portion of a liquid or gas; the rates of passage of gases through porous membranes as influenced by the molecular weights of the gases; magnus effect; and many others. These possibilities, although known theoretically, need considerable exploratory and physical research before their practical limitations become known.

Among the chemical processes and phenomena offering possible solutions to the problem, there are three principal ones. One is known as ion-exchange.

As applied to demineralization of water, it involves the removal of both the cation and anion of the dissolved salt by exchange for a less objectionable ion in the exchange material.

The cations are replaced usually by the hydrogen ions, producing acids with the anions remaining in solution. The acids are in turn exchanged by the anion exchange material, resulting in the formation of an amount of water equivalent to the salts removed. The process differs from the softening of water, in which only the cations of calcium and magnesium are exchanged for sodium with no net decrease in the total dissolved materials.

In the process, for every equivalent amount of salt removed, a corresponding amount of regenerating chemical must be supplied. Consequently, this might be best adapted to the demineralization of waters of low saline concentration or to partial demineralization where only the most harmful salts are removed. The use of clay or other natural beds of inexpensive ion exchange material is being explored as a possibility for the reduction of costs of operation of this process.

Chemical precipitation of mineral materials in saline water is used extensively in water-treatment plants for industrial or potable use. The quantities of chemicals required for precipitation, however, are approximately equal to the quantities of salts removed. Thus, for large-scale demineralization of saline water, the quantities of treatment chemicals would be very large and prohibitively expensive. Recent advances in chemical precipitation have improved existing processes for such uses as emergency life-raft equipment. The greatest promise here is in the removal of some specific components only.

The formation of insoluble hydrates by the addition of chemical substances to saline water is another chemical possibility. Withdrawal of water from saline solutions by hydration of chemical compounds, and its later release as pure water by dehydration is possible. Water may be recovered by changing the process variables, such as temperature or pressure.

Saline water is itself an electrolyte. This suggests the possibility of demineralization by electrolysis—a method that has been used to soften water.

When an electric current is transmitted through a saline solution, the cations of the salt molecules in the solution migrate towards the cathode and the anions toward the anode. Several quite dissimilar devices have been introduced to provide means of causing the moving ions to collect with other ions within the cell and be washed aside in a reject stream, while an ion-depleted stream is drained off separately. Several such devices are already in laboratory use. Two firms conducting research on devices using this principle, with some promise for an ultimate commercial unit, are Rohm & Haas and Ionics, Inc. The latter has assembled a unit now being tested on typical brackish waters in the western part of the United States.

Electrolysis of a saline solution generally results in evolution of hydrogen at the cathode and either oxygen or chlorine at the anode. The catholyte becomes basic by removal of the hydrogen ions, and the anolyte becomes acid. Hydroxides of elements, such as calcium and magnesium, precipitate in the cathode chamber, the precipitation being the basis for a water-softening process when the anode and cathode are separated by a porous diaphragm. A similar cell, divided into three compartments, provides a means of demineralizing salt water entering the central compartment, the dissolved salts being progressively removed to the adjacent compartments.

The combination of selective ion-transfer membranes with electrolysis provides a rather new demineralization process. During the formation of any quantity of product in an electrolytic process, equivalent amounts of ionic constituents are transported into the electrode regions. This same quan-

tity of material must pass through any plane parallel to the electrodes. In an electrolytic cell, the space between electrodes may be divided by a number of membranes, which possess the property of permitting the passage of a cation or anion, but not both. If the anion-permeable and cation-permeable membranes are arranged alternately, one method of demineralization is obtained. By such an arrangement, salts will be removed from alternate compartments and transferred, through one membrane, to adjacent compartments from which they cannot migrate electrically, but may be removed hydraulically. Hence, the water passing between alternate membrane pairs is depleted of salt, while that between the intervening pairs is enriched. The quantity of electric power required for removing a given quantity of salts is a function of the number of compartments, the resistance of the unit, and the rate of hydraulic flow.

Some additional electrical phenomena have been suggested as being susceptible to use for demineralization. They encompass the electrostatic and electromagnetic effects, ultra-high frequency currents, and others. Of these, only the latter has been reported as being observed actually to reduce the salt concentration of saline water. That remains to be proved on a more scientific basis, however.

Until recently many of the processes and phenomena we have mentioned were primarily something of interest in the classroom, laboratory, and text books. Urged on by the increasing demand for more fresh water, they are becoming recognized as useful ideas. Those that are developed for practical use will provide means of compensating for the adjustments man has made in the patterns established by nature.

It would be presumptuous to foretell a degree of success in this endeavor. Exactly when practical use can be made of the fruits of today's research in this field is almost as difficult to predict. Some processes will probably require several years to perfect; others may reach a reasonable degree of usefulness earlier. It does appear, however, that no one process by itself will be likely to provide water to meet the needs of the Nation. Several will be required to fulfill the variety of demands dictated by local conditions.

But development of a technically and economically feasible process will be a help cure for one of mankind's greatest and growing ills—insufficient fresh water.

DAVID S. JENKINS *became director of the Saline Water Conversion Program, Department of the Interior, in 1952, when it was authorized by the Congress. The Saline Water Conversion Program is conducted by grant and contract under the direction of a staff in the Office of the Assistant Secretary of the Interior for Water and Power. Previously Dr. Jenkins was successively with the United States Geological Survey, Soil Conservation Service, Civil Aeronautics Administration, and the Bureau of Reclamation.*

R. J. MCNIESH *was formerly a general engineer, Saline Water Conversion Program, United States Department of the Interior. He joined a construction firm in St. Paul, Minn., in 1955.*

SIDNEY GOTTLEY *is executive assistant to the assistant director for programs, Bureau of Mines, Department of the Interior. He is a representative of the Bureau of Mines on the Saline Water Conversion Committee.*

In further recognition of the growing water shortages throughout the United States and abroad, the Congress has, subsequent to the preparation of this chapter, enacted amendatory legislation to the Saline Water Act of 1952 extending the activity until 1966 and increasing the total authorization from 2 million to 10 million dollars. In doing so, it provided that a limited amount of work may be conducted in existing Government laboratories and a considerably smaller amount may be expended on research abroad where that research clearly contributes to the solution of problems in the United States.

The Age-Old Debate About a Forked Stick

Arthur M. Sowder

Few subjects are more hotly debated than water dowsing. Few activities are more stoutly supported by their practitioners (of whom I am one in my spare time) or more roundly ridiculed by others. On the one hand are the words and experiences of those who have used a forked stick themselves to locate underground water. On the other hand is a large body of scientific investigation and writings, which say flatly that water dowsing is pure nonsense and without any valid basis.

The purpose of this essay is to tell both sides without trying to convince the reader one way or the other. No discussion of water can be considered complete without a mention of this ancient debate.

At various times I have had opportunity to experiment and discuss dowsing with people, some of whom were dowsers. I learned that not many can dowse and that those who can, do so in varying degrees. Those who cannot generally assert scoffingly that dowsing is faked by hand manipulations.

I have tried forked twigs of many species of woods, and each seems to work, but twigs of peach, apple, and maple seem to be best. I grasp the ends of the twig firmly with palms upward. As I start, I have the butt of the stick pointed up. As I near moving water, I can feel the pull as the butt end begins to dip downward. When I am over the water, it is straight down, having turned through an arc of 180 degrees. A stick of brittle wood will break under my grip as the butt dips downward. Pliable twigs will twist down despite efforts to hold them straight.

Now, SOME EXCERPTS from published works to indicate the pros and cons.

Interested persons will do well to read Water-Supply Paper 416, *The Divining Rod, A History of Water Witching*, by Arthur J. Ellis. It was published in 1938 by the United States Geological Survey.

In an introductory note, Dr. O. E. Meinzer wrote: "The outline of the history of the subject presented in the following pages will probably enable most honest inquirers to appreciate the practical uselessness of 'water witching' and other applications of the divining rod, but those who wish to delve further into the mysteries of the subject are referred to the literature cited in the bibliography, in which they will find reports in painful detail of exhaustive investigations and pseudo-investigations of every phase of the subject and every imaginable explanation of the supposed phenomena.

"It is doubtful whether so much investigation and discussion have been bestowed on any other subject with such absolute lack of positive results. It is difficult to see how for practical purposes the entire matter could be more thoroughly discredited, and it should be obvious to everyone that further tests by the United States Geological Survey of this so-called 'witching' for water, oil, or other minerals would be a misuse of public funds."

Nearly half of the booklet is devoted to a bibliography arranged in chronological order back to the early 16th century.

Mr. Ellis wrote:

"The origin of the divining rod is lost in antiquity. Students of the subject have discovered in ancient literature many more or less vague references to it, and though it is certain that rods or wands of some kind were in use among ancient peoples for forecasting events and searching for lost objects, and in occult practices generally, little is known of the manner in which such rods were used or what relation, if any, they may have to the modern device. The 'rod' is mentioned many times in the Bible in connection with miraculous performances, especially in the books of Moses. . . ."

In an article in Arizona Highways for June 1954, Gaston Burridge wrote:

"I have been interested in the dowsing phenomenon for nearly 40 years, not as a participant, for I have none of the dowser's powers, but as an observer. I think I have seen every kind of locating device there is, from a common willow fork, up through and including a $10,000 'electronic' machine! I believe I've listened to as many methods, heard as many theories, as many explanations, as many experiments as any man in the Southwest. I have witnessed 'map dowsings,' 'long-distance dowsings,' have been on actual locating jaunts for water, oil, minerals and buried treasure. I've heard of all sorts of 'mistakes' dowsers have made. I have taken the trouble to do some investigating and now I can match those tales with 'mistakes' both well drillers and geologists have made!

"Most dowsers I have met believe the dowsing instinct, ability, power, 'atunement,' or whatever it is, comes to a person with birth. But they also believe this innate ability can be developed, its use expanded, by study and practice. Many people have the ability but don't know it, never having had reason or opportunity to try it. Some students of the matter believe about 1 person in every 1,000 has some dowsing ability, that 1 person in about 10,000 has enough of the ability to become a good dowser. And I would like to point out right here, there is a vast difference between a dowser and a good dowser!"

KENNETH ROBERTS in his book, *Henry Gross and His Dowsing Rod* (Doubleday, 1951), wrote:

"Not all the derision of all the geologists in the world can in any way alter the unfailing accuracy of the dowsing rod in Henry Gross's hands. Not all the cries of 'hokum,' 'curious superstition,' 'fanciful delusion,' 'hoax,' 'witchery,' 'pseudo-science,' can destroy or even lessen the value of Henry's dowsing, to whose unvarying success Horace Levinson and I have attested by the publication of this book. . . .

"The man who sneers at the dowsing rod today would have scoffed, 50 years ago, at radio, television, and jetplanes that travel at supersonic speeds."

MR. ROBERTS' BOOK was reviewed by Thomas M. Riddick in an article, "Dowsing Is Nonsense," in Harper's Magazine for July 1951. Mr. Riddick, a member of the American Water Works Association, wrote: "If this book on dowsing indicated that Henry Gross possessed unusual powers, explainable or not, which enabled him to locate extractable underground waters, I would be a most ardent supporter of his cause. But this indication, much less this proof, is lacking. And to accept Mr. Roberts' beliefs necessitates a complete disregard of the basic principles of hydraulics, hydrology, meteorology, physics, thermodynamics, and geology, and even the fundamental laws of gravitation."

AND SO IT GOES.

Space does not permit a complete listing of the references on the subject of dowsing. Some titles, though, indicate the way the subject has been treated: That Dowsing Hokum; Water Witching: An Interpretation of a Ritual Pattern in a Rural American Community; A Dowser Talks Back; The Problem of the Divining Rod; All-Purpose Dowsing; Can a Water Witch Really Find Water?; and Witching Wands and Doodlebugs.

The controversy will continue until someone can explain and prove the action of the dowsing stick.

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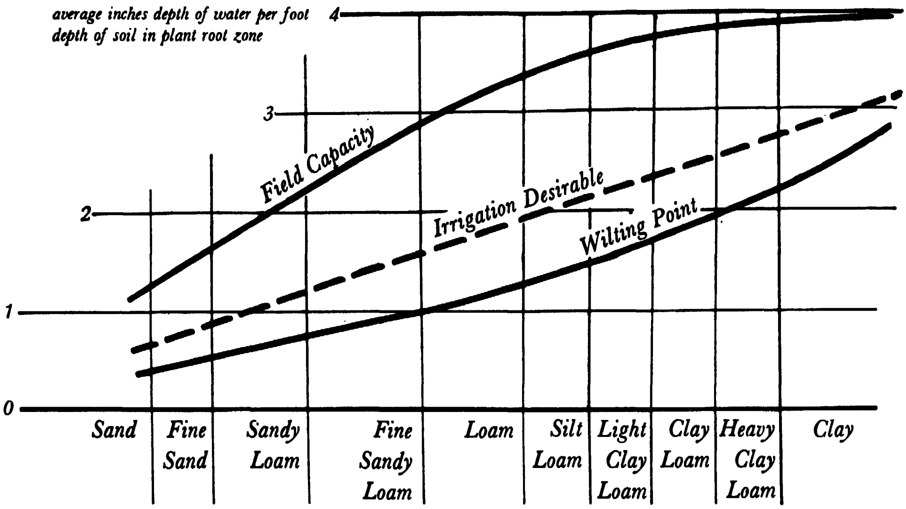
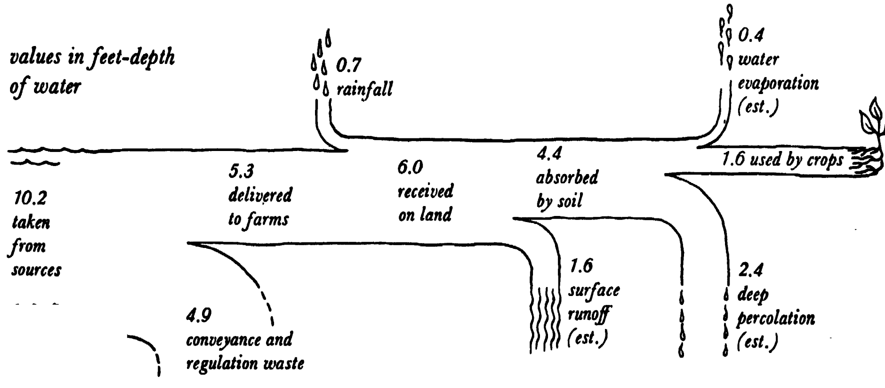
Typical Water-Holding Characteristics of Different-Textured Soils



Disposal of Water Diverted and Pumped for Irrigation in One Western State in 1949



Water and Our Soil

How Water Shaped the Face of the Land

Guy D. Smith and Robert V. Ruhe

Before men began to use the soil of this country it did not matter at all how much or how little water the land got. It matters now, though, for the water or the lack of water did produce characteristics in the soils that still persist and must be considered when we farm them today.

In the natural landscape, before the soils were used, water influenced the soil directly by erosion. As a weathering agent, water attacks and dissolves minerals, moves soluble materials in solution and insoluble materials in suspension from one part of the soil to another, and removes materials entirely in the ground water. Indirectly water affected the kinds of plants that grew, the rate at which they grew, and the micro-organisms that decomposed the leaves, stems, and roots of the dead plants. Water therefore had an important part in determining the kind and amount of organic matter in the soil and all of the physical and chemical properties that are affected by organic matter. The amount of water a soil received was influenced in turn by the rainfall, humidity, wind, and the other factors of climate, as well as by the shape of the land surface and by the underground features that affected the movement of water.

Water, wind, ice, and gravity can detach and transport earth materials. Of the four, running water is the most important in modifying the earth's landscapes.

Rain begins the work of running water in that the impact of raindrops alone on unprotected soil can dislodge soil particles and commence the wearing away of the land.

Rainfall is dispersed in two ways: By infiltration—soakage into the ground—or runoff at the surface. The relative amounts of infiltration and runoff are determined by the nature of the rainfall, the slope of the land, the character of the local soils and rocks, and the nature and amount of vegetation.

Hard, severe rains produce high runoff. The steep slopes are conducive to runoff. Permeable soils and rocks give rise to greater infiltration than do less porous materials. A sparse cover of vegetation favors runoff.

Runoff in unconfined channels is sheetwash, which can remove large amounts of material on slopes that are barren or have a sparse vegetation.

Runoff that is confined, whether in rills or streams, has a concentrated erosive effect, cutting channels that may increase in length and depth at a rapid rate. Such stream erosion may give rise to spectacular landforms, such as gullies, badlands, or even large canyons.

The cutting and intrenchment of a

stream immediately develops three elements of the landscape: The channel bottom, the valley slope, and the upland. The fourth element, the pediment, develops later and is the gently sloping surface that lies between the stream and the valley slope after the valley slope recedes from the stream.

Of these four elements, the valley slope, because of its steeper gradient, is most susceptible to erosion by complex processes.

The channel bottom may undergo a further but continually decreasing modification as the stream adjusts itself toward the base level of erosion, the level at which water can no longer flow and transport any material. The channel bottom affords a major control within its watershed in that it is a general base level of erosion for all tributary streams. Because the valley slope leading down to a watercourse cannot be eroded below the level of the streambed, the general base level of erosion for the valley slopes is the level of the main stream.

The fundamental mechanism in the evolution of a landscape by water erosion is the recession of the valley slope into the upland, regardless of climate, but the process is most obvious in the desert. Valley slopes along the main stream, tributaries, and the side streams are subjected to an intensive attack by various processes, such as gullying, sheetwash, slumping, and sliding. The dominance of any process depends on the nature and intensity of rainfall, the character of the valley slopes, the character of the local soils and rocks, and the nature and amount of vegetation.

The major control of erosion is the main stream, whose streambed tends to become increasingly flatter toward its mouth. Such gradients are characteristic also of the tributary and side streams. Valley slopes recede so that the pediments, the land surface between the valley slopes and the streams, have lesser slopes nearer the streams.

Thus the general base level below which erosion cannot progress is a curved surface, which is controlled by the main stream and rises upward with increasing gradient toward the edges of the watershed. This curvate landscape, scooplike in form, is characteristic of most watersheds, regardless of size, and can be considered the "normal" landscape unit developed by water erosion.

If hard rocks are present, a layer of transported gravel, called the stone line, develops on the pediment as it is formed. The stone line usually is covered by variable thicknesses of finer textured sediment, the pedi-sediment. In the final phases of erosion, valley slopes retreating from adjacent streams meet and disappear, joining the pediments and producing a lower regional surface, the pediplain. The process of pediment formation is called pedimentation. (See page 141.)

Many kinds of soil-moisture relationships existed in nature, but four of them largely determined the kinds of soil found by the first settlers. They might be called, for simplicity, those of the desert, the prairie, the forest, and the swamp.

In the desert the very low rainfall and high evaporation kept the soil dry most of the time. An occasional downpour moistened the soil at the surface and at times some water may have moved down a few feet before it was withdrawn by the roots of plants or evaporation.

Soluble materials near the surface were either carried away by the runoff or moved down into the soil with the water and were deposited where the water was withdrawn. Rapidly soluble materials, like soda, were the first to be moved. Then limestone fragments near the surface were slowly dissolved, and the lime was redeposited in a deeper layer. That redeposited lime, called caliche, accumulated both as massive hardpans and as soft, white powder and was the first evidence of soil development in our deserts. Caliche is normally found on the uplands and is common on the pediments.

After the caliche was partly formed, the occasional percolating waters began to move part of the clay (very fine particles usually less than .00002 inch in diameter) in suspension from the surface layer into the subsoil. The clay was deposited in the subsoil just above the caliche as fillings in pores or cracks. The movement of clay, however, was very slow compared to the movement of lime, and soils that show a horizon (a layer in the soil parallel to the surface) of clay accumulation are less common than soils with horizons of caliche.

Low areas where the runoff waters collected and evaporated were enriched with the soluble salts. Although they often had moisture available most of the year, the water was so salty that only the most salt-tolerant plants could grow.

The desert soils generally could support only scattered shrubs because the soils were dry so often, and little organic matter (generally less than 5 tons to the acre in the plow layer) ever accumulated in the soil.

Not only did the low amounts of rainfall result in slow soil development; the infrequent heavy rainfall on surfaces with a poor vegetative cover stripped the surface materials from the valley slopes and deposited some of that material on the pediments. Erosion or deposition often was more rapid than weathering and soil formation. Thus the erosion-weathering relationship accounts for the generally weak soil development in the desert. And the rainfall-vegetation relationship accounts for the curious paradox that in the natural landscape the most spectacular erosion was in the desert where there was the least water.

In the prairie, bordering the desert, the soil was moist for longer periods and became covered with a close-growing grass sod. The rainfall was adequate to support the grass, but only in the wettest years was there a surplus of water to saturate the upper layers of the soil and percolate below the reach of the grass roots. The result was the formation of a soil marked by a thick, black, or very dark brown surface layer, with large contents of organic matter—up to 100 tons to the acre in the first 6 or 7 inches—and underlain by a layer (or horizon) in which slowly soluble materials like lime accumulated.

After the lime had been dissolved and removed from the surface layer, many of the minerals in rocks became unstable, lost their alkaline elements, such as calcium, and were chemically altered to clay. Such changes were very slow and required a stable land surface for many hundreds of years to be noticeable. If the upland surface was stable, part of the clay formed in the surface foot or so was gradually carried in suspension by the percolating water into the subsoil. There the clay particles were filtered out or the water was withdrawn by plant roots, and the clay was deposited as a coating along the channels in the soil. The process of clay translocation continued on many of the flat upland surfaces until the pores and channels in the subsoil were clogged with clay. Then the water, unable to enter the subsoil readily, formed a perched water table above the subsoil. Subsoils that have reached such a point in clay accumulation are called claypans.

Natural erosion was very much slower under the grass sod of the subhumid prairies than in the deserts. Raindrops did not strike the soil but lost their energy on the grass. Total runoff was considerably greater than in the desert, but the running water had less chance to detach soil particles on the valley slopes, and the waters of the streams were generally clear.

The shapes of the landscapes, the occurrence of stone lines, and the presence of the most strongly weathered soils on the divides indicate that the natural erosion in the prairies, as in the desert, was pedimentation. Further evidence of pedimentation is found in the widespread loess (a deposit of windblown particles ranging in diam-

eter from about 0.002 to 0.0002 inch) in the midwestern prairies, which generally mantles the uplands but is absent from most valley slopes. This loess mantle also bears witness to the stability of the upland surfaces under the grass sod. The studies of the radioactive carbon in wood buried in the loess show that it began to accumulate about 25,000 years ago and that it continued to accumulate for about 15,000 years. So it has persisted for some 10,000 years on the undulating uplands—even where it originally was never more than 2 or 3 feet thick.

In the forests, which extended from the prairies to our coasts, the rainfall was generally high enough that nearly every year some water percolated through the soil and on down to the ground water. On stable land surfaces, all readily soluble materials were completely removed, and the soils consist of materials practically insoluble in water. Minerals containing the alkaline elements, such as calcium, magnesium, and potassium, required for the growth of plants, are unstable in these moist soils and were gradually altered to more stable forms. While the soils were young, the decomposition of the minerals yielded a slow, steady supply of available plant nutrients. The slow replenishment of nutrients is generally still going on in the soils formed in deposits laid down during the last great advance of the glaciers. The deposits covered most of New York, New England, the area north of the Ohio River, a belt some 30 to 50 miles wide to the east of the Mississippi River bottoms, and part of the State of Washington.

In most of the remainder of the forested areas, the soils are much older and contain few weatherable minerals. Here the alkaline elements needed by the plants were held largely in their leaves and wood and were used over and over again. The plants had a constant struggle to capture and retain elements against leaching by the water.

The minerals that were weathered were largely transformed to clay and iron oxides, which are relatively insoluble in water. The formation of the clay and iron oxides started at the surface and continued downward as the rocks weathered, sometimes to depths of several scores of feet. While the weathering progressed in the deeper layers, at the surface there was some solution of the iron oxide by the organic compounds coming in the water from the leaf litter. Redeposition of this iron followed, sometimes only a few inches below the surface, and sometimes deep in the soil. But since it is the iron oxide that makes the soils red or brown, when the iron was removed the surface became bleached and gray.

The clay particles in the surface foot or two were also removed, probably in part by destruction of the clay but also by being carried in suspension by the downward moving water into the subsoil. There it was filtered out or was deposited on the walls of pores and cracks when the water was withdrawn by the tree roots.

Thus in the forest region there gradually developed a series of horizons, or layers, which differed in color and clay and iron content, as a result of the continued leaching by water. The surface inch or two was stained with organic matter from the leaf mold. The next layer was bleached and had such small amounts of clay that it was neither sticky nor plastic when moist. The third layer was browner or redder than the second because of the accumulation of iron oxide. In most places outside of northern Michigan, northern New York, and New England, this third layer had enough clay to make it sticky and plastic when moist. Underlying that was the weathered or unweathered rock or other material from which the soil formed.

The processes of natural erosion under the forests have not been studied in detail in this country, but the evidences cited in the prairie region are duplicated in the forest region and point again toward pedimentation. We do know that there has been cyclic gullying followed by filling of many of

the gullies in many areas, but the general deep weathering of the soils suggests that natural erosion was much slower than the weathering processes.

IN THE SWAMPS AND MARSHES the water table stood near the surface for at least a part of each year.

In places where the water table was above the surface, the remains of the sedges, reeds, and trees were protected from decay by the water and accumulated to form peat or muck.

If the water table stood at or just below the surface during a large part of the year, generally a slow but significant downward movement of the water took place. Then the soils that formed had many properties in common with those of the nearby uplands, but they differed in one important respect. Oxygen was lacking in the stagnant water, and the iron tended to be more readily soluble. It was therefore removed altogether or was concentrated into small, hard, buckshotlike pellets or massive ironstone and bog iron ore. The place of accumulation depended on the water movement, for the iron moved slowly but steadily with the water.

THE WHITE MEN who first tried to use the soils were on our eastern coast in the forest region, where the percolating waters over the ages had removed most of the plant nutrients not held in the trees themselves. The early settlers tried to farm by methods they had used in western Europe, where the nutrients had been concentrated on the arable land by centuries of manuring with compost from the stables, mixed with litter from the forests and sod cut from the common pastures. In the new country, where these same practices were used, farming was difficult and crops were indifferent, but a permanent agriculture was started. In places where reliance was placed on cash crops, such as cotton and tobacco, the few nutrients held by the forest were quickly exhausted or leached from the soil. Since fertilizers were unknown, a shifting agriculture was adopted in which a field was cleared and cropped for a few years until yields declined; then another field was cleared. The swamps were avoided because more suitable land was available for the clearing, and methods of drainage were unknown or too costly.

Cultivation spread slowly westward to the edge of the prairies. There it was stopped for a short time by the grass sod, which the plows of the time could not break. When the steel moldboard plow was introduced and the prairie sod could be broken, cultivation spread rapidly across the plains. The homesteaders used the wet lands for meadow and pasture and cultivated only the better drained areas where water never stood. Since few plant nutrients had been leached out of the soils of the prairies, crop yields were excellent, and production of grains soared. Naturally fertile soils could be had for the taking, and many farms were abandoned which had been producing grain on the leached soils of the Northeastern States. Cotton and tobacco continued to be grown in the Southeastern States largely because the arts of the manufacture and use of fertilizers had been discovered in Europe and introduced into this country. Fertilizers came into use about 1850, and their use was the first widespread modification of a deficiency caused by water.

Toward the end of the 19th century the bulk of the better farm land had been settled, and major emphasis in agricultural expansion shifted from breaking the prairie and clearing the forests to more intensive use of land in farms. The swamps, marshes, and peat bogs, scattered over thousands of farms and occasionally concentrated in large areas, presented the best opportunity for agricultural expansion. The state of mechanical arts made earth-moving machinery and drain tile available, and drainage was started on a large scale. Ditches were dug so as to furnish outlets for the water, some streams were straightened, levees were built, tiles were laid, and the bulk of the

naturally fertile wet soils were brought under cultivation by about 1910.

During that period and shortly after, the easiest lands to irrigate were developed and the last frontier was reached.

Now we must learn better methods of controlling erosion and increasing infiltration in many parts of the country and how best to use the soils already damaged by erosion, and how to use the limited irrigation water in the West most efficiently.

But we have made great strides in solving equally difficult problems in the past, and we can look forward to solving the new problems.

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How Rainfall and Runoff Erode Soil

Ben Osborn

The erosive actions of water are the effects of the energy developed by its movement as it falls toward the land in the form of rainfall or over the land as runoff.

The distinctive actions of raindrops and surface flow derive from the different directions in which their force is applied to the land surface. Raindrops strike the soil from a vertical direction. Flowing water moves horizontally over it. The nature of the work done and the direction in which dislodged particles are moved are different. Their effects are known as splash erosion and scour erosion.

Splash erosion is the first effect of a rainstorm upon the land. The falling drops gouge and splatter the exposed soil like many little bombs. They shatter clods and granules and reduce them to particles. They lift soil into the air and splash it back and forth. After the land becomes covered with water, the raindrops create turbulence in the sheet flow and help keep the dispersed materials in motion.

Effects of the splashing action can be seen everywhere after any hard rain. Soil clinging to foliage or to the foundations of buildings attests to the great quantities moved by raindrop actions. Pedestals of soil, each capped by a pebble or other object which protected the area beneath, reveal the extent of soil removal. If the pedestals conform in cross section to their protecting covers and are not undercut from the sides, the erosive force was applied primarily from above by raindrops, rather than horizontally by runoff.

The dead weight of 1 inch of water on an acre is more than 110 tons. The weight, falling as countless drops in a hard rain and often driven by violent winds, strikes with terrific force. The

impact furnishes a major part of the energy for erosion.

The total energy of raindrops has been calculated as being equal to roughly 100 horsepower on an acre during rainfall of 0.1 inch an hour and 250 horsepower at 2 inches an hour. The latter is sufficient force to lift the 7-inch topsoil layer to a height of 3 feet 86 times during an hour's rain, equivalent to 518 million foot-pounds of work.

This might be 1,000 to 100,000 times the kinetic energy of the shallow sheets of runoff water that result from the same storms. Runoff frequently is as little as 10 percent of the rainfall and on gentle slopes may move at velocities of 0.3 to 3 feet a second, compared to about 30 feet a second for the falling drops. The force of falling raindrops may be 10 thousand times the energy of the surface runoff in hard summer storms, even on steep slopes.

Erosive capacity of raindrops results from three factors: Amount and intensity of rainfall, the diameter of the drops, and the velocity of the drops as they strike the soil. Velocity varies with size of drops after they have fallen far enough to reach maximum speed.

An inch of rain falling as large drops in a hard thunderstorm has many times the erosive capacity of an inch of fine drizzle that lasts several hours.

Drops vary in size from the finest of mist to those nearly 8 millimeters, or one-third inch, in diameter. Drops larger than that separate into smaller ones as they fall.

Any rain consists of drops of many different sizes, with more large drops in the harder rains. The median size varies from 1.47 millimeters at an intensity of 0.1 inch an hour to 4.25 millimeters at 10 inches an hour.

Speed of the falling drops varies with their sizes. The larger ones, 3 to 6 millimeters in diameter, reach near-maximum velocities of 26 to 30 feet a second after a fall of 24 to 26 feet in still air. Practically all drops in natural rain are falling at maximum velocity when they strike the ground. If wind is present, their speeds may greatly exceed the terminal velocities that are due to gravity.

The amount of soil set in motion by a single drop is directly proportional to the square of the velocity of the drop. A certain minimum impact is necessary to initiate soil movement. A drop 1 millimeter in diameter falling at its terminal velocity of about 10 feet a second will move fine sand particles.

The amount of soil detached by rain depends on the force of the rain, or its detaching capacity; the character of the soil, or its detachability; and the protective value of any cover present.

The force of the rain can be measured by exposing a uniform soil material to the drops under standard conditions and determining the amount of soil removed in any unit area. A fine sand, whose particles are 0.175 to 0.250 millimeter in diameter, has been used as a standard for the studies.

Such measurements revealed a detaching capacity of 338,000 pounds an acre for a 3.8-inch rain in Tennessee. At San Angelo, Tex., the detaching capacities of rains during one 2-year period ranged from amounts almost too small to detect to a maximum of 115,200 pounds an acre. The rain of maximum detaching capacity was not the largest rain, but one of high intensity. It was accompanied by a driving wind.

The susceptibility of soils to dispersal by raindrops is variable. The ease with which a given soil is set in motion affects the amount of splash erosion under any set of conditions where raindrops strike bare ground.

Detachability is influenced by the permanent characteristics of the soil type, such as the size and the shape of particles. Most readily dislodged are particles of fine sand. Coarser sands are less easily detached because of the greater size and weight of the particles. Soils of finer texture are less detachable because of the aggregation or cohesion of the particles. Shape affects detachability through differences in the degree of interlocking of the particles.

Temporary or changeable conditions of a soil, such as structure, content of organic matter, moisture, or tilth due to tillage, also affect its detachability. It is not unusual to find greater differences between rates of detachability of different samples of the same soil type than between averages for the different types.

Splash from bare cropland plots by a standardized application of water that has a detaching capacity of 110,000 pounds an acre has varied from 33,198 to 225,565 pounds of soil an acre. On bare range and pasturelands, soil splash under similar raindrop impact varied from 8,832 up to 160,339 pounds an acre.

Soil samples from croplands, compared to the standard sand as 100 percent, have had index values of detachability ranging from 30 to 205 percent. The same soil types in ranges and pastures had detachability rates of 4 to 106 percent.

Puddling and sealing of the land surface is another effect of the impact of raindrops on bare soils. The force of the drops breaks down the loose crumbs at the surface. As moisture penetrates the soil, the cementing materials are softened and the lumps disintegrate by slaking. Air may be trapped inside clods and aggregates in some soils. Pressures built up by compression of the air aid in breaking them down into individual particles.

The churning action of the drops on the surface beats the dispersed material into a pasty mass. Pores and channels through which the water otherwise would travel are soon plugged. In the violent shifting of the particles on the surface, finer ones are fitted between the coarser ones to make an impervious seal. Even on coarse sands, the interlocking of the surface particles reduces the intake of water.

Direct compaction of the soil by the force of the drops also occurs. Up to two-thirds the energy of the falling drops may be used in ramming and compressing the surface soil.

The effect of those actions is virtually to waterproof exposed land surfaces during the first few minutes of a rain. In tests with artificially applied rainfall, runoff from bare plots has started in 1 to 4 minutes from the beginning of application. As much as 95 to 98 percent of the applied water, even on sandy loams and sands, was lost as runoff.

The sealing of the soil surface prevents infiltration and storage of moisture for plant growth and crop production. The water accumulating on the surface provides the runoff that carries away the detached materials and makes floods.

The plant cover on the land offers natural resistance to the splash process. To the extent that it intercepts the drops before they strike the soil and absorbs their energy, it reduces the amount of soil detached.

To obstruct the vertical force of the raindrops, the important property of the cover is its ability to provide a complete canopy over the land. That is done by the litter lying on the ground or by standing vegetation, provided it is not tall enough that water dripping from the foliage will have enough impact to cause splash. This "umbrella for the land" is quite a different function of cover, requiring different characteristics, from that of retarding surface runoff.

Effectiveness in reducing soil splash is proportional to the amount of cover present at the time the rain occurs. Both the thoroughness with which the land surface is covered to shield it from the drops and the weight and bulk of the cover present to absorb the energy of the rain are important.

Amount of vegetation is more important than the kind in its role of soil protection, although the differences in growth form of plants account for some differences in protection. Effective (95 percent) control of raindrop energies requires approximately 2,000 pounds the acre of short sod grasses, 3,500 pounds of ordinary crops or bunchgrasses, or 6,000 pounds of tall crops and weeds. Soil-protective values

Soil particles and globules of mud are hurled in all directions when a water drop strikes wet soil.

decline rapidly as the amount of cover declines below those levels.

Transportation of detached soil materials through space is the second step of the erosion process. Soil transportation, like detachment, is work performed by the energy of the moving water. Detachment is measured in amount per unit of area, as pounds or tons on an acre, but transportation must be measured in amount through distance, as pound-feet or ton-miles.

The amount of transportation possible is limited by the energy available to do the work and by the amount of soil already detached and available for transport.

Raindrops are relatively unimportant in the transportation of the detached materials, although the cumulative effects under some conditions may be considerable.

The soil particles and droplets of soil-charged water that are thrown into the air travel varying distances in all directions from the point of impact of each drop. On level ground when the drops strike from a vertical direction, the effects tend to cancel one another, leaving the same amount of soil on the area at the end of the rain. But such conditions are uncommon; the slope of the land and direction of the wind give a predominant direction to the travel of the splashed soil.

Laboratory experiments, in which individual drops were made to strike standard sand at different angles of slope, indicated that the percentage of detached material moving downhill amounts to 50 percent plus the percentage of the slope. Because particles thrown downhill travel a greater distance before coming to rest than those splashed uphill, the splashed soil is gradually shifted downward, even on relatively gentle slopes. Measurements in an open field of 10-percent slope showed 3 times as much downhill as uphill movement of splashed soil.

The amount of soil transported by raindrop splash is governed by the transporting capacities of the raindrop energy, the ease with which the detached materials are carried, and the resistance offered by the vegetation or other obstructions.

The energy available for carrying the detached particles is the difference between the total force of the impact and that used in dislodging the particles and compacting the soil mass or dissipated in other ways. That varies with the individual splashes, partly in accordance with the size of the particle or aggregate set in motion. In normal rainfall, soil is commonly thrown to a height of 2 or 3 feet, and to a horizontal distance of 5 feet. But large aggregates several millimeters in diameter are moved only a few inches, and larger pebbles are barely lifted clear of the surface or turned over by the impact. The distance is further affected by whether travel is downhill or uphill and whether it is with or against the wind.

Plant cover interrupts the travel of the splashes. Measurements of soil splashed onto forage in badly overgrazed pastures in Tennessee revealed as much as 700 pounds of soil per ton of oven-dry vegetation after some rains. That undoubtedly was only a small part of the splashed soil caught by the vegetation, for the rainfall continues to wash down the intercepted material during the storm. Of course, cover that is dense enough to prevent raindrops from striking the earth and setting soil in motion in the first place effectively prevents soil transportation.

Other controls might be effected by

modifying the surface condition of the land. For example, close-spaced parallel ridges at right angles to the slope might overcome the downhill movement of splashed soil on a bare field. Then the angle of impact of the individual drops would direct about equal portions of the splash upward and downward with respect to the general slope.

Surface seal on a core sample of freshly plowed cropland after a 20-minute test application of water drops by a raindrop applicator.

Runoff water is the second erosive agent of the rain. When rate of rainfall exceeds the intake capacities of the soil, water that is not absorbed where it falls moves across the land as surface flow. It gains energy as it travels downslope, and it also dislodges and transports soil.

Runoff water sets soil in motion by a process of scouring. Its effects are evident mainly in the form of rills and gullies.

The amount of soil movement effected by surface flow, like that by falling drops, is a result of the energy of the runoff, the susceptibility of the soil to detachment and transportation by this agent, and the resistance or protection afforded by cover or artificial structures.

The energy in the surface flow derives from its movement downslope. Velocity and turbulence are expressions of this energy. The capacity of runoff to erode therefore depends on the amount of water involved and the slope and configuration of the land over which it moves.

Runoff takes the form of sheet flow, or shallow layers of water spread more or less uniformly over the land surface, and channelized flow, which is concentrated into defined watercourses. The distribution of the energy and the resultant types of erosion differ for the two forms. The former, coupled with raindrop actions, produces sheet erosion. The concentrated scouring action of the channelized flow causes rill and gully erosion.

Sheet flow acts on broad field areas between the rills and gullies, usually more than 95 percent of the land surface. Its effects are gradual and often go unnoticed until most of the topsoil is removed. Changes in color or texture or reduced plant growth are common symptoms of sheet erosion.

As excess water begins to collect on a smooth surface during a rain, it is without kinetic energy. As the water moves downhill, it gains velocity in accordance with its depth or volume and the amount of vertical fall. Velocity increases with the distance of flow, or length of slope, since each increment of length adds to the amount of water and the fall.

Such sheets of water on a smooth surface move at first as laminar flow without turbulence. The energy present is only that of the velocity of translation, and is seldom of consequence in soil movement. As the depth of flow increases, turbulent patches form and travel downslope. The frequency of the patches increases with increased depth and velocity, until the entire flow is turbulent. The turbulence is accompanied by a great increase in kinetic energy and erosion capacity.

The normal depths attained by sheet flow under normal field conditions are usually very shallow. Measurements of sheet runoff at rates of 1.25 to 3.68 inches per hour on bare plots of up to 20 percent slope and 116.7 feet length showed depths of flow ranging from 0.06 to 0.15 inch. This agrees with other calculated depths of overland flow as it reaches channel edges. Grass

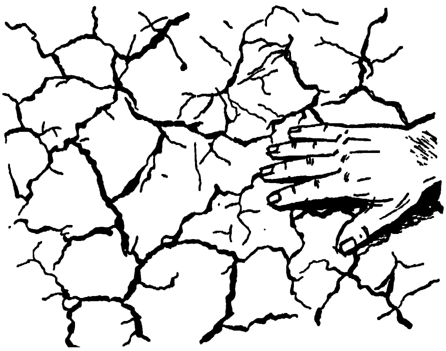
or crop cover by retarding runoff increases its depth by as much as two to five times. Even so, sheet flow outside of channels seldom exceeds a fraction of an inch in depth.

The impact of falling drops contributes greatly to erosion by such shallow flows. The direct action of the splashes is reduced by as little as 0.1 inch of water, but the energies of the falling drops are transferred to the surface flow in the form of turbulence. Strong vertical velocities in the water are directed downward to detach the soil and upward to support the detached materials. Under similar conditions, sheet flow may carry large amounts of soil, especially of the finer fractions and lighter organic and soluble materials, without sufficient horizontal velocity to be significantly erosive itself. Water standing on a level surface during a hard rain has been found to contain 20 percent of suspended soil. The movement of such muddy water, even on the gentlest slopes, would remove large amounts of soil.

The energies inherent in the surface flow are greatest on the steepest slopes and increase downward on each, but those imparted by the impact of raindrops are uniformly distributed horizontally over the land. It is through the combined actions of raindrops and sheet flow that rainstorms are able to remove fairly uniform layers of soil from large areas.

Channelized flow develops when irregularities in the land surface concentrate the water along certain lines of flow or obstructions create turbulence that increases the scouring action of the runoff. As the amount of water in the channels grows, the velocity and turbulence increase. Minor rills coalesce downslope to form larger ones, and the runoff is progressively concentrated in streams of greater violence. Thus larger and larger proportions of runoff energy are directed against smaller and smaller portions of land surface.

The scouring action of concentrated flow carves out rills a few inches wide, which are obliterated by tillage operations. The rills grow downslope into larger channels. As the cutting and transporting proceed, rills grow into gullies too large to be crossed. Not only are large volumes of soil removed from the beds and walls of the channels and carried downstream, but the landscape itself is dissected and agricultural operations are made difficult or impossible.



The surface crust on bare soil after rain shows how the impact of raindrops and slaking forms an impervious layer.

The channelized flow removes soil by scouring along the lines of its travel, and, because of its great concentrations of kinetic energy, carries away the detached soil fed into it by sheet flow and raindrop splashes. The development of rills and gullies in a field, therefore, greatly accelerates the removal of soil from the entire area.

The dissection of a slope by channels, however minor, has the effect of reducing the length of slope for the sheet flow. Overland movement begins at the top of each slope or at the divide between two rills, and it ends where the water enters the channel. As each new channel develops, the distance of prechannel flow in that part of the field is cut in two. The volumes and velocities and consequently the total energies involved in the sheet flow are thereby reduced. Because of the natural irregularities in most land surfaces, channelization occurs promptly wherever there is much runoff.

Scour erosion, like splash erosion, consists of the two distinct steps of detachment and transportation. But the different distribution and direction of the energy involved result in different effects.

Runoff energies, acting parallel to the land surface, are most efficient in soil transportation. The detached materials are all moved downslope.

The scouring action of runoff sets soils in motion without compacting the surface. Because most of the detaching capacity of runoff is found in the channelized flow and the detached materials do not leave these streams, its scouring action normally does little to muddy the water on the general land surface. Surface flow therefore seldom cuts infiltration capacity by clogging the soil channels as do raindrop effects.

Detachment by runoff consists of three kinds of actions—rolling, lifting, and abrading.

When flowing water moves across a smooth soil surface, horizontal forces act upon particles in the direction of the flow. The forces may be enough to dislodge particles from the soil mass by rolling or dragging them out of position. That action is detachment by rolling.

A rough soil surface contains many small depressions between clods and crumbs. The water in the depressions may have little or no horizontal velocity, while that just above may be flowing rapidly. The different velocities set up pressure differences which cause vertical currents and eddies. The upward movement of the water past soil particles lifts them from their moorings and sets them in motion. That is detachment by lifting.

Soil detachment by abrading occurs when particles already in transit in the flow strike or drag over particles in the soil surface and set them in motion. This form of detachment is peculiar to the scouring action of runoff, and accounts for a large part of the erosion initiated by it.

The detaching capacity of surface flow, then, varies with the kinetic energy of the flow and the presence of abrasive materials in the water. The energy present is a function of volume of flow, velocity, and turbulence, all of which increase downslope and reach their greatest proportions in the channelized flow. The energy imparted to shallow sheet flow by raindrop impact adds to its capacity to detach soil.

Depth also is a factor in the soil-moving capacities of shallow flows. At depths found under field conditions at the beginning of the erosion process, the greatest movement of soil occurs when the depth of flow is about equal to the diameters of the soil particles to be moved.

The abrasive action of the runoff depends on the amount of suspended materials in the flow and the abrasive quality of the materials. The amount of soil detachment by a flow of constant energy can be varied by changing the amount or kind of abrasive materials in it.

Transportation of the detached soil materials is the major result of runoff in the total erosion process.

The amount of materials carried and the distance from points of detachment at which they are deposited are important considerations. The amount of soil passing the lower boundary of an experimental plot or a field is a significant measure of the soil "lost" from the area, but it is not a measure of the amount of soil transportation performed by the runoff.

Surface flow moves soil by surface creep, saltation, and suspension.

The same horizontal forces that dislodge particles by rolling or dragging may keep them in motion by rolling or sliding them along in contact with the land surface or stream bed. Such movement is known as surface creep.

Movement by saltation occurs when the uneven forces of turbulence lift the detached materials free of the bed and move them along by steps or jumps. As the particles rise into the more rapid flow above, they gain

velocity, which causes them to detach other particles or to bounce back into the flow themselves upon striking the bed again. A continuous downstream movement of either the same or different particles thus occurs by a succession of short hops or jumps.

When the upward velocities of turbulence in the flow exceed the settling velocities of the detached materials, transportation by suspension occurs. Particles lifted into the body of the fluid may be given repeated impulses by the turbulence and may travel long distances before returning to the bed.

The amount of soil transported in any situation is a product of the transporting capacity of the runoff and the transportability of the soil, as modified by the retarding effect of vegetation or mechanical obstructions.

The amount, velocity, and turbulence of the surface flow govern its transporting capacity, as they do its detaching capacity. Since velocity increases as the same amount of water becomes more and more confined, soil materials that find their way into gullies and streams may be carried great distances before they are detained by obstructions or deposited by the stilling effects of decreased bed gradients or impoundments.

The transportability of the detached materials influences the distance they can be carried by the energy present in a given flow. The same properties that make a soil easily detached may not necessarily make it easily transported; in fact, the reverse frequently is true. This factor is related to the rates of settling of the particles in suspension and is considered to be a result of their size, density, and shape.

The size of a particle affects its total weight or mass and consequently the amount of energy required to keep it in motion. Its cross-sectional area also governs the extent of contact with the supporting fluid and the resistance offered to its settling. Density affects the rate of settling, and thereby the distance a particle is floated each time it is splashed or scoured into suspension.

Shape also has a direct influence. Spheres have the highest settling velocities, size and density being equal, and therefore the lowest ability to be carried. Angularity and lack of roundness increase resistance to settling. In general, the further a particle departs from the spherical shape, the longer it will remain in suspension. When particles are so large and dense that they are transported by the process of rolling, projecting corners and broad, flat sides keep them from moving as freely as round ones.

Plant cover protects the land from the scouring action of runoff by offering resistance to the moving water and shielding the soil from its effects. Because of the horizontal, rather than vertical, direction of the erosive force in runoff, however, different properties of the vegetation are involved in counteracting scour erosion than in preventing splash.

To oppose the flow of water, the plant parts must be within the depth of the flow. To offer maximum resistance, they must be perpendicular to its line of movement. A canopy of foliage a few inches above the ground, which might be highly effective in intercepting raindrops, would have no value in impeding runoff. Numerous fine stems, spaced closely together, provide the greatest protection.

It is not true that vegetation, bent over and completely submerged by flowing water, shingles the soil and forms a protective shield. Observations through glass walls in experimental channels lined with different plant covers have revealed that vegetation remains standing up in the flow, waving and whipping back and forth. Its main effect is to retard the velocity of the flow near the soil surface. Greatest retardance is obtained from a dense, tall, uniform stand of sod-forming vegetation. Stiff stems, which resist bending, help retard the flow.

Cover for the control of runoff needs to be anchored to the soil, a feature not important in controlling splash.

Growing or standing vegetation therefore is superior to most mulches or litters, which might be floated and carried away by the runoff.

RAINFALL AND RUNOFF form a team of erosive agents that are most efficient and destructive when they work together. We have seen how rainfall is more important in detaching soil and runoff in transporting it, although each causes the other action to some extent.

Whichever of the two integral steps of detachment and transportation is performed to the lesser degree limits the total erosion and resulting land damage. The presence of both creates the greatest hazard.

A unique example of the action of runoff in the absence of raindrops is the erosion caused by snowmelt. Severe rilling of steep slopes sometimes occurs when rapid melting frees water faster than it can be absorbed by the soil. The tendency of surface flow to concentrate in channels, with its scouring action confined to the lines of flow when unaided by raindrops, is plainly seen in the characteristic erosion patterns resulting from snowmelt.

When the ground is frozen beneath the thawing surface layer, the upper few inches of soil may become so saturated with water that it moves downslope in the form of a mudflow. This form of erosion is in response to forces of gravity, independent of the energy of moving water. It is related to other forms of creep on steep slopes, the caving of gully banks, and similar mass movements of soil under the force of gravity.

DEPOSITION is the end of the erosion process. The moving particles come to rest when the kinetic energy of the raindrop splashes or runoff is spent or where vegetation or mechanical obstructions resist the erosive forces.

Because of the short distance of travel of the individual particles in splash erosion, the distribution of the deposited material conforms closely to the erosional activity of each storm. Only through the cumulative effect of the downslope migration of particles repeatedly splashed do deposits from raindrop actions become significant.

But deposition of erosional debris in unwanted places is one of the major damages resulting from erosion by runoff. Fertile soils below upland slopes and in bottomlands are often covered with the less productive fractions of the materials that are carried down by runoff. Crops and pastures are damaged by soil deposited on them by floodwaters. Streams are clogged and reservoirs reduced in storage capacity by sedimentation.

Thus accelerated erosion is doubly destructive. It damages the land at the point of removal and at the point of deposition. The beneficial results of deposition, as in building up of alluvial soils, are generally the slow work of normal geologic erosion rather than the more violent processes made possible by man's disturbance of natural protective covers.

PROTECTION FROM EROSION is obtained by the resistance of vegetation or mechanical structures to the energies of rainfall and runoff. Such protective measures prove most effective when they retard the erosional element, which is already limited in each case.

Since detachment precedes transportation, the entire erosional process can be forestalled by preventing this initial event. A cover of vegetation can be produced and made to achieve this effect on lands of agricultural value.

Artificial mechanical structures have been used to reduce or to control the effects of runoff. They include field terraces, various forms of dams and diversions, and the performance of tillage operations on the contour to leave ridges and furrows at right angles to the direction of flow.

All those measures serve primarily to reduce the velocity of the runoff, thereby reducing both its detaching and its transporting capacity. To the extent that they impound parts of the runoff and allow more time for its in-

filtration as it passes over the land, they also reduce the amount of water in the surface flow. Thereby they limit the work performed by this erosive agent, but do not directly reduce the activity of raindrops.

In field situations where runoff is doing most of the erosion and is the limiting factor on soil movement, those measures effectively reduce the total soil loss. On the other hand, if raindrop action is the critical factor, reducing the velocity of the runoff does not prevent the erosion damages.

Mechanical obstructions to runoff may reduce or prevent soil movement beyond the boundaries of a field without materially reducing the total soil movement within it. On soils of high detachability during rainfall of sufficient force to load the runoff to the limit of its transporting capacity, the structures may actually interfere but little with total erosional activity. While each terrace interrupts the flow and causes it to drop its load of soil, the runoff originating in the interval below is free to pick up a new cargo of detached soil. The results are seen in the benching of terraced land that is not also protected by adequate cover.

In most field situations, a combination of mechanical measures and plant cover designed to meet the peculiar combination of erosion factors operating on that particular land area is necessary for effective control.

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Valleys and Hills, Erosion and Sedimentation

L. C. Gottschalk and Victor H. Jones

Erosion is the natural process that has sculptured many of the features of our landscape. The forces of Nature, including water, ice, wind, and gravity, strive constantly to wear down the uplands and build up the lowlands.

Erosion has been occurring throughout geological history. Whole mountain systems have been eroded away, and little evidence remains of their existence other than the consolidated, stratified deposits that we find in sedimentary rocks.

Charles Butts, who completed a study of the geology of Virginia in 1940, believes that about 60,000 cubic miles of mud, sand, and gravel were deposited during the Paleozoic era of geologic time in the geosyncline that constitutes the Appalachian Valley of

Virginia. The deposit in places is 8 to 10 miles thick. If it were spread over the area of Virginia southeast of the Blue Ridge, from which much of it probably was derived, it would raise the level of the State to 10,000 feet above sea level.

Some forms of geologic erosion are so spectacular that they leave awe-inspiring chasms like the Grand Canyon of the Colorado, or remnants like the colorful spires of Bryce Canyon and Zion Canyon. Anybody who sees them can have no doubt about the tremendous force of uncontrolled water in carving away the surface of the earth.

Other forms of erosion occur so slowly that it is hard to recognize them. The flat prairies, the rolling hills, and the steeply sloping valleys may be erosional remnants of a much higher land in former geologic times.

In the light of geologic history, man represents the peak of biological development. Since the retreat of the last continental glacier in North America, marking the close of the Pleistocene epoch, the very short time of 10,000 to 20,000 years has spanned the greater part of human history. In the United States we are primarily concerned with man's occupancy and influence on erosion during the past 300 to 400 years.

The effects of rapid growth in our population and the intensive use of land have been profound. The natural geological processes of erosion have been accelerated in many sections. Soils, which required many centuries to form, may be eroded away in a single rainstorm because of improper land use. Over that kind of rapid erosion man can exercise a certain amount of control.

Because the erosion may occur as a result of sheet flow or confined flow in a watershed, we classify and measure sources of sediment according to sheet erosion and channel erosion.

The rate of sheet erosion depends on the inherent erodibility of soils, the length of slope, degree of slope, land use, and the intensity, duration, and frequency of rainfall.

Different soils have different inherent rates of erosion. The presence of organic matter, amounts of colloids, and depth to less pervious subsoil affect inherent erodibility—the natural tendency of soil to wash away. Results of plot measurements show that erosion varies with 1.35 power of the degree of slope expressed in percentages; the 0.35 power of the length of slope expressed in feet, and the 1.75 power of maximum annual 30-minute rainfall in inches.

Analyses of the effect of land use on the loss of soil at Pullman, Wash., indicate that cover is one of the most important elements that influence the amount of erosion. It also is one of the most variable. A plot that loses soil at the rate of 100 tons an acre under fallow or up-and-down-hill cultivation might lose only 10 tons if it is planted to small grains, 2 tons if it is in good pasture, and less than 1 ton if it is in good forest cover.

When we apply the results of the plot studies to existing conditions in the United States, we would find soil losses as high as 200 tons an acre a year from fields where intertilled crops are planted on highly erosive soils with steep and long slopes. That is equal to more than an inch of soil removed.

The figures on plot measurements are useful as a basis for delineating the main sheet-erosion areas in a watershed and for selecting and locating land-treatment measures to reduce downstream damages due to sediment from sheet erosion. Such a computation of sheet erosion, adjusted for watershed conditions, also provides a reliable means for developing design criteria for sedimentation in small reservoirs.

Channel erosion leaves obvious scars. The amount of material removed from a watershed by channel erosion can be determined readily by measuring the voids of channels. The rate of erosion of a gully can be determined by measuring the volume of material removed and establishing the age of the gully.

Similarly, the amount of erosion of streambanks, valley trenches, the road

ditches, flood-plain scour, and other types can be determined. Aerial photographs taken of much of the country in 1938, 1939, and 1940 are invaluable in determining the rates of channel erosion by comparison with present conditions.

The relationship of the sheet erosion and the channel erosion to the total erosion in a watershed varies from place to place, depending on the local conditions. The bulk of sediment in humid agricultural areas generally is derived from sheet erosion; in arid and semiarid areas it comes mostly from channel erosion.

EROSION, transportation, and deposition of sediment together are called sedimentation. The three are important in the control, use, and maintetnance of our water resources. The removal of the absorbent topsoil exposes the less pervious subsoil and causes runoff water to flow off rapidly and aggravate downstream flood problems. Erosion of topsoil reduces the fertility of soil and its ability to maintain a good protective cover. Runoff water, heavily laden with sediment, must be clarified by special processes before it can be used for domestic and industrial purposes. Sediment deposited in reservoirs occupies space needed to store water for such purposes as flood control, power, irrigation, domestic water supply, and recreation.

When stream channels become plugged with sediment, above-normal flows spill over the banks and create floods. Silting in irrigation canals and drainage ditches reduces their ability to move water. Navigation channels must be dredged periodically so that vessels may move without grounding. Sedimentation seriously affects upstream engineering. Unless it is given adequate consideration in the planning, development, and use of water resources, the engineering projects may lose their usefulness.

TRANSPORTATION of sediment occurs in two ways. As suspended load it is distributed throughout the cross section of flow. As bed load it slides, rolls, and bounces along the bed.

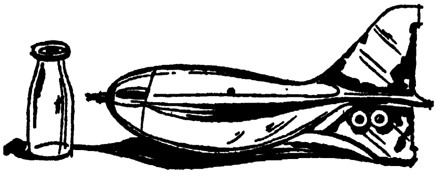
The clays and colloids generally are evenly distributed throughout the cross section of flow. Silts are also distributed throughout the cross section in turbulent flow but normally have a tendency to increase in concentration with depth of flow. Coarse sands, gravel, cobbles, and boulders usually are rolled along the bed; under conditions of high velocity and turbulence they may become suspended in the load above the bed.

The nature of material in transportation is largely influenced by the sources of sediment. Sheet erosion removes mostly the finer materials from the soil. In places where the main source of sediment is from sheet erosion, therefore, the sediment derived is fine in texture and moves as suspended load. Those materials are referred to as the wash load of the stream. Measurements of sediment loads of streams in the Midwest show that often 90 percent or more of the sediment is transported as suspended load. In places where channel erosion is the major source of sediment, the sediment is mostly coarser grained and is transported mainly as bed load.

The amount of wash load moving through a reach of stream is related to the rate of supply rather than to the ability of the flow to transport such materials. Wash load travels with the same velocity as the flow and is seldom present in quantities equal to the capacity of the flow. Wash load therefore is seldom deposited in the main channels and has a minor part in channel stability.

But the amount and types of bed load moving through a reach of stream is related directly to the flow. Because the movement of bed load is always in balance with flow conditions, it has an important bearing on the stability of channels. If the flow becomes overloaded with bed materials, deposition occurs. If the load is less than the flow can carry, it immediately attacks the channel walls in an effort to satisfy the

balance. Any conditions that change the sediment load or flow characteristics will have a corresponding effect on channel stability. Thus the stability of channels may be affected when dams or other control works desilt the flow or change the flow characteristics by altering the discharge, the stream gradient, cross section of flow, or depth of flow.



A depth-integrating, suspended-load sampler. The milk bottle is placed in the sampler, and the sampler is submerged in the streamflow by means of a cable. The vanes keep the sampler pointed upstream. The sample is taken into the bottle through the nozzle projecting in front of the sampler. The rate at which the bottle fills varies with the stream velocity.

Sediment in transit may cause minor damages associated with the cost of removal of clays and colloids from suspension and the abrasive effect of sediment-laden water. Before water can be used for domestic or industrial purposes, clays and colloids must be precipitated or filtered by the use of special chemicals and processes. Some industries, among them the rayon industry, require water with an unusually low amount of suspended matter. All suspended matter must be removed from drinking water before it is considered potable. The abrasive effect of sediment-laden water takes its greatest toll on hydroelectric power-generating equipment, where it causes excessive wear on turbines.

Not all of the material eroded in a watershed is moved out. The bulk comes to rest below slopes and on flood plains. It is estimated that less than one-fourth of the materials eroded from the land surface in the United States ever reach the oceans.

The amount of sediment carried out of a watershed is known as the sediment yield. The ratio of sediment yield to gross erosion is the delivery rate. The delivery rate of a watershed depends on the size of drainage area, the amount and character of runoff, the topography of the watershed, the degree of channelization, and other factors, which determine the ability of the stream system to pick up and transport sediment.

The delivery rate of the large, gently sloping watersheds with few channels is low. Usually less than one-fourth of the material eroded in such watersheds is transported out. Conversely, the delivery rate of small, steep, highly channalized watersheds is high. More than one-half of the eroded materials from this type of watershed may be transported out.

Sediment yields from watersheds are measured by sediment-load measurements and reservoir sedimentation surveys.

Sediment-load measurements consist of taking periodic samples of runoff water to determine the concentration of sediment in the flow. Special samplers have been developed for such work. Relating the concentration to the discharge provides a measure of the load. Because both erosion and runoff are related to the extent and character of rainfall in the watershed, sediment load normally increases as the discharge increases. By plotting the sediment load against discharge, one can develop a sediment-rating curve for each measuring station. From the curve the long-term sediment yield of a watershed can be estimated from existing long-term discharge measurements. The method is commonly used to determine the sediment yield for large watersheds.

Long-term sediment yields of watersheds may also be determined by measuring the accumulation of sediment in reservoirs of known age. Special equipment has been developed to determine the thickness of deposits and the volume-weight relationship of the sediment. The volume of sediment is measured by standard hydrographic

survey methods. The yield is determined by converting the volume of sediment to weight of sediment on the basis of the volume-weight relationships of the deposits. As there are difficulties in getting representative sediment-load samples from the flashy runoff of small watersheds, reservoir sedimentation surveys provide a good way to measure the yield of sediment from them.

Because of the many complexities of soils, the topography, land use, runoff, channelization, and other conditions in watersheds, sediment yields vary widely. Anyone who designs a reservoir for the utilization of a water resource must know the sediment yield of the watershed in order to provide for sedimentation in the design. If adequate storage for sediment is not provided, the reservoir may silt up rapidly and lose its usefulness long before the period for which it has been designed. Knowledge of the sediment yield from watersheds is also needed in the planning and design of navigation channels, harbors, irrigation canals, drainage ditches, and other works of improvement in order to develop proper design and predict maintenance costs.

The sediment yield of a watershed depends primarily on the size of the drainage area. C. G. Holle estimated in 1952 that the sediment yield of the Mississippi River watershed above the delta amounted to about 500 million tons a year. Studies by the Corps of Engineers indicated that the average load of sediment of the Mississippi in the delta area consists approximately of 7 percent sand, 38 percent silt, and 55 percent clay. Preliminary data in the files of the Soil Conservation Service indicate that the rivers of the United States carry about 1 billion tons of sediment to the oceans each year.

Comparison of the rates of sediment movement from watersheds can best be made on the basis of the rate of sediment production per unit of drainage. On the average the rate of sediment production per unit of drainage declines as the size of drainage area increases. Greater variations in rates of sediment production are found for small watersheds than for large watersheds, because greater contrasts in watershed conditions exist for the smaller watersheds. The rate of sediment production for the Mississippi Basin amounts to about 400 tons for each square mile of drainage. A rate of 97,740 tons to the square mile was measured from a small watershed in the Missouri River Basin in western Iowa.

Deposition of sediment is the counterpart of erosion. It occurs when the carrying capacity of flow is reduced to the point where transport is no longer possible. The basic laws that apply to erosion and transportation of sediment apply to deposition of sediment.

When flow is diminished, the coarser sediments are deposited first. Thus deposition, like erosion, is a selective process, which results in gradation of deposits. The main types of sediment deposits that are delineated in watershed work include colluvial deposits, alluvial fans, channel deposits, floodplain deposits, lake and reservoir deposits, estuary and harbor deposits, and deposits in oceans.

Colluvial deposits commonly form below sloping lands that have been cultivated without conservation controls. The environment may be at the foot of upland slopes, on the edges of alluvial valleys, or on slopes leading downward to the shores of lakes or oceans. The typical form of a colluvial deposit is long, narrow, and sinuous.

The origin of colluvial deposits is primarily sheet erosion. They represent a lag-type deposit, which has traveled only a relatively short distance from the fields from which they were eroded and deposited when the flow becomes insufficient to transport them farther. In many places they are intermingled with materials from mass movement down the slopes. Damages that are associated with such deposits are due primarily to the changes in texture and fertility of the soil that affect productivity. A large portion of

the material carried out of fields by sheet erosion remains in the watershed in the form of colluvial deposits.

Alluvial fan deposits usually form below tributary streams of main valleys or along a mountain front, where sudden changes occur in the transport capacity of flow. The changes usually are associated with abrupt changes in the gradient of the tributary stream or the pondage effect of flood flows in the main valley. The bulk of the material of alluvial fans generally originates from tributary channels. It may include sediment of practically all textures, from clay and silt to coarse gravel. Substantial damages occur in several different ways as a result of fan formation: Rapidity of deposition, which buries crops; coarse sediment, which lowers the fertility of the areas of deposition; and topographic changes upon the alluvial plain. An example of such topographic changes is to be seen in valleys in areas of glacial till, red beds, and sandy areas where the fans have impinged on valleys and channels of main streams, changed their courses, and increased the flood heights.

The channels of various river systems commonly are of two categories, degradational and aggradational. In the channels where incision or downcutting is predominant, the deposition of sediment from accelerated erosion generally is not a serious problem, except in local instances. Some youthful streams of this type, especially those now cutting canyons, have not developed alluvial flood plains.

Most streams having alluvial valleys are in a relatively stable condition or are actively building flood plains at normal, slow, geologic rates. Overloading streams with debris from accelerated erosion, changes in character of runoff, and stream meandering are the main causes of deposition in stream channels. The deposition of the sediment has caused serious problems in many alluvial valleys and channels. Deposition of sediment in the stream channels has filled or partly filled the channels with sediment. The result is most conspicuous in headwater areas.

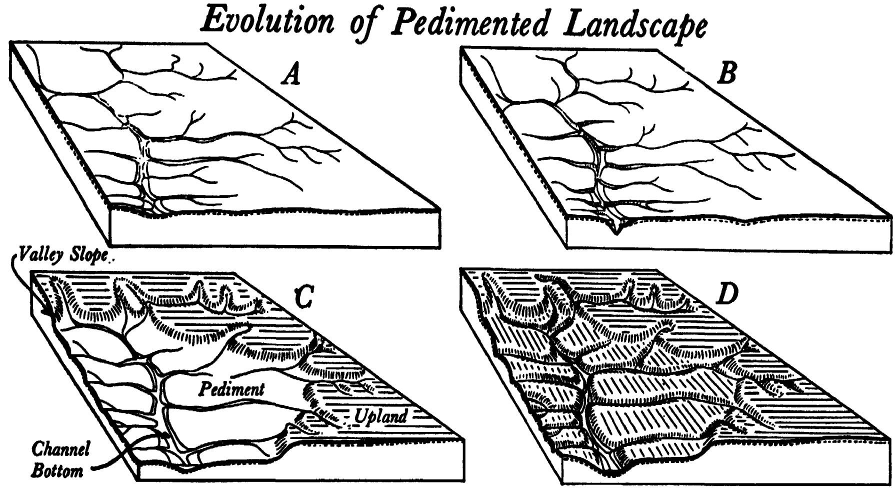
The consequent decline in capacity and increase in elevation of channels has resulted in a number of types of damage—an increase in flood heights and areas inundated, elevation of the ground water level and a consequent spread of swampy areas, blocking drainage outlets, impairment of flow of water in irrigation canals and drainage ditches, restriction of navigation, a decline in value of the streams as reliable sources of water supply, and damage or destruction of such recreational facilities as fishing and swimming.

The deposition of sediment from accelerated erosion has occurred on the flood plains of hundreds of stream valleys in the country. It is one of the major sedimentation damages found in our watersheds. Deposition occurs when sediment-bearing streams spill out of their channels and spread over the adjacent flood-plain areas. Types of deposits on flood plains include natural levees, flood-plain splays, and broad lateral accretion deposits. The deposits bury crops, change the character and fertility of flood-plain soils, and impair the natural drainage.

Lakes are relatively temporary features of the landscape. Geologically they have a relatively short life. All lakes, natural and artificial, are subject to deposition, which in time will fill them. Artificial lakes or reservoirs are a major item in the development of water resources.

The reservoirs are designed to store water for use during periods of low flow or for retarding the rate of flow during periods of abnormal runoff. In either instance, the maintenance of storage capacity is vital in their successful use and operation.

Because reservoirs reduce the carrying capacity of flow to practically nothing, nearly all of the sediment in transport, when it enters a reservoir, is deposited in the reservoir basin. Reservoirs with small capacities and built on streams carrying large loads of sediment rapidly lose their capacity.



Four steps in the evolution of a pedimented landscape: A is the emplacement of the drainage system on the landscape; B, The drainage system cuts into the land and the first three elements of landscape begin to develop—the channel bottom, the valley slopes, and the upland; C, The valley slopes recede and the lower-level pediment, mantled by stone line and pedi-sediment, develop. The landscape becomes a curved surface, scooplike in form, concave upward toward the edges of the watershed. The removal of the older weathered zone on the pediment exposes the fresh parent material to a new cycle of soil formation. D, the second-cycle cutting of the drainage system. New valley slopes begin to recede from the channel bottoms. If conditions are favorable, weathering is continuous on the original surface during changes from (A) to (D) and results in the formation of deep, well-developed soils. (See also pages 121–126.)

Related damages include depreciation of property values, cost of modifications to power or water-supply plants, and damage to recreational facilities.

The deposition of sediment in bays, estuaries, and harbors is a natural process. It has been hastened by our present program of land use. Many problems arise from the deposition of river-transported sediment in bays and harbors and along the coastlines.

Dredging to maintain harbors and channels is costly. Deposition alters the character of barrier beaches and causes maintenance problems in intracoastal waterways. Oyster production has suffered where deposition has created muddy conditions or forced the upper limit of brackish waters seaward.

Sediment deposited in ocean margins along the continent occurs mostly along the edge of the submerged continental shelf. In relation to land use and sediment deposition, the major process affecting the coastlines is growth of deltas, such as that of the Mississippi River. Delta formation in coastal zones of gently shelving continental shelf areas at the debouchures of major rivers is a characteristic process. Deltas, such as those of the Mississippi, the Rhine, the Nile, the Amazon, and the Orinoco, have had a major part in human history. The present chief concern of coastal and harbor problems is to maintain such delta areas for the valuable and useful purposes that depend on them.

One major change in the formation of deltas has developed from control of the rivers and harbors in the delta areas. For example, the lower Mississippi River now is confined within levees, which are nearly continuous downstream all the way from Cairo, Ill. Floods that formerly spread widely over the delta area below Baton Rouge are confined mostly within the levees. The present growth of the delta therefore is toward greater length and lesser width. Both water and sediment are carried by the stream within the levees

past New Orleans, and much of the delta area that formerly received periodic deposits of sediment is now subsiding as the sediments become compacted.

Before adequate sediment-control measures can be developed, it is necessary to determine the source, amount and nature of damaging sediment. Thus, if damage is caused mainly by fine materials resulting from sheet erosion in a watershed, we have to put into use the types of land treatments recommended for the reduction of sheet erosion. If the damaging sediment consists primarily of coarse materials and the sediment is derived from channels, measures to stabilize the channel are needed.

Measures needed to control sheet erosion are designed primarily to provide protection of the soil against the impact of raindrops and reduction of rapid runoff. The most effective and important means of reducing sheet erosion is by using the land properly and improving the cover of vegetation. Land too steep for cultivation should be put into pasture or woodland. Land not suitable for continuous row crops should be placed in rotation with other crops such as small grains and meadow to maintain productivity of the soil and to provide protective cover for a good part of the time.

The protective cover of range and forest lands can be improved by revegetation and by proper use and management. Erosion losses from sloping land may be further reduced by decreasing the effective length of slope. That can be done by contour cultivation and terraces, which intercept the runoff at regular intervals down the slope and prevent it from building up to erosive flow.

Methods for reducing channel erosion are designed on a basis of altering the discharge, the cross section, depth of flow, gradient, or other conditions that cause erosion or by accepting unaltered flow and protecting the channel against it. Not all problems of channel erosion are solved easily. For example, the shaping and seeding of a waterway may be all that is needed to halt erosion of a small gully, but an expensive drop inlet structure may be required to stop erosion of a large gully. Economics obviously may determine the limits of control that can be justified.

One of the measures for reducing channel erosion is by regulating flow. That is done by retarding reservoirs, which impound excess runoff water and release it slowly to downstream channels. The realinement, shaping, and revetment of channels may be done if the discharge cannot be controlled and if the damages justify the cost. Sills are a good way to stabilize the grade of a channel and reduce bed degradation. Bank erosion may be controlled by using revetments or altering the direction of flow. Finally, channels may be drowned out and erosion reduced by strategically placed reservoirs and drop inlet structures.

If it is not possible physically or economically to control sediment at its source, the construction of sedimentation basins may be required to reduce the damages from sedimentation. The basins may be designed to trap silt, sand, gravel, and even large boulders. Basins often are built to provide temporary relief from sedimentation damages until control can be installed and become established at the source. Periodic excavation of sedimentation basins is required in many instances, or new basins must be built to provide long-term protection.

One way to reduce excessive deposition of sediment loads in channels is to design channels that maintain sediment in transit. Changes of channel alinement, which involve modification of meanders, have been made in many valleys in an attempt to avoid excessive deposition.

Channels have been straightened in hundreds of valleys of all sizes, but most of the results have been undesirable. The excavation and straightening of meandering channels (many of which contain large sediment deposits)

usually have resulted in a great increase in erosion by the stream. That, in turn, has meant a great increase in downward incision, new areas of bank cutting, and excessive subsidence of the water table. Artificial ways of making a channel narrower can increase the velocity of flow, but they involve complex engineering structures. Other mechanical means of controlling stream and current involve the use of vanes and deflectors, chiefly at bends.

EFFECTS OF WATERSHED programs on the yields of sediment from watersheds have been measured for a number of watersheds in the United States. In places where extensive measures have been installed, the yield of sediment has been reduced correspondingly.

An example of the reduction in sediment yield is on Lake Issaqueena, near Clemson, S. C. The 14-square-mile watershed above the reservoir is in a section of the Piedmont Plateau that once was badly eroded. Before the first sedimentation survey of Lake Issaqueena in 1941, few erosion-control measures had been installed on the watershed. Between 1938, when a dam was built, and 1941 the average annual rate of sediment production amounted to 2,400 tons to the square mile. Between 1941 and 1949, when a second survey was made, the proportion of the watershed having reasonably good protection from erosion increased from 53 to 73 percent. The 1949 survey showed that the average rate of sediment production for the second period had dropped to 1,150 tons to the square mile annually—equal to a reduction in sediment yield of more than 50 percent of the rate for the first period.

A similar study in 1952 showed that measures to improve the watershed and control erosion had effected a reduction in sediment yield of 33 percent from the watershed, which covers 1,666 square miles, above Lake Waco, near Waco, Tex. Results of resurveys of reservoirs by employees of the Soil Conservation Service showed a reduction of 78 percent in the sediment yield from the watershed, of 1.39 square miles, above Lake Newnan in Georgia; a 27-percent reduction from the 62.3 square miles above High Point Reservoir in North Carolina; and a 43-percent reduction in sediment yield from the drainage area of 7.29 square miles above Roxboro Reservoir in North Carolina.

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Retention and Transmission of Water in Soil

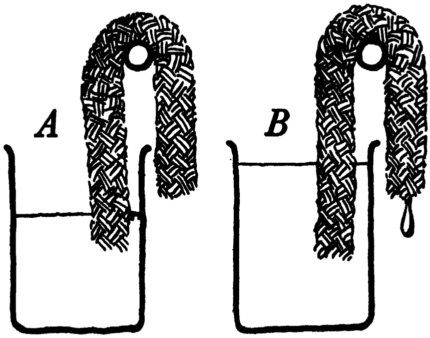
L. A. Richards

Soil in the root zone is a complex medium. Physical and chemical properties vary tremendously from one soil to another and from one point to another in the same soil profile. If attention is focused on the fact that the physical properties of water are essentially the same in all soils, however, progress can be made in applying laws of hydrostatics and the principles of the dynamics of viscous flow. The applications are commonly made for ground water where the soil is saturated, but in the root zone where the soil is unsaturated the applications are not widely known or appreciated. The case of hydrostatics—the pressure for equilibrium of liquids—can be illustrated by the following device.

Wet a piece of clean cheesecloth with water and crumple it into a porous roll about 1 inch in diameter and 8 inches long. Hang the roll over a rod and mount a beaker with the water at the same level as the free end of the wick, as shown in the accompanying sketch. Surface tension action will cause water in the wick to come quickly to equilibrium with the water in the beaker. Pressure increases with depth below the free surface and can be expressed in terms of pressure head. This is the length of vertical water column required to produce the pressure at the point in question. In static water systems, all points at the same level have the same pressure. The pressure head at any level in the beaker is the difference in elevation between the point and the reference level where the pressure is equal to that of the atmosphere. Where the pressure is greater than the reference pressure, the pressure head is taken as positive.

The water in the wick will likewise be at static equilibrium with the free water surface. All points at the same elevation above the reference surface will have the same pressure, which will be less than the reference pressure and hence will be negative. This corresponds to negative pressure head, and for unsaturated soil it is convenient to use the term "suction head" instead of the equivalent negative pressure head.

Water elevated in the wick is not bounded on all sides by a solid surface, but there exists an air-water interface. This will occur mainly at the exterior surface of the wick but at higher elevations it will extend in a complicated fashion through the interior also. At each height, the curvature of the interface adjusts to the value required to give the correct suction head, as determined by the vertical distance to the free water surface. Water that is added to the wick will quickly drain back into the beaker, so that the previous static curvature relation is restored. If the free end of the wick is only slightly above the flat water surface in the beaker, the air-water interface at the end of the wick can be observed to be only slightly concave. The curvature adjustment can be checked by adding a small amount of water to the beaker so that the free end of the wick extends below the free water surface. This requires that in order to reestablish static equilibrium, the pressure in the free end of the wick must be positive. This corresponds to convex curvature



Surface tension action in a wick illustrates hydrostatic balance and viscous flow in soil.

in the air-water interface, and under this condition drops will form and fall from the end of the wick—an illustration of the special hydraulic boundary condition that has important application to soils. Free water outflow from soil will not occur when the water is under suction. Water will not move from soil into a drain tile, nor will it drip from a flowerpot or lysimeter, until the suction is reduced to zero.

The term "water table," as used in soil work, is defined as the locus of points in the soil-water system at which the water has atmospheric pressure. In the wick, at the static condition, this corresponds to the elevation of the free flat surface, and the suction head at each point in the wick is just equal to the vertical distance above the water table. That also holds for soil. If no water table is present, then at static equilibrium under gravity the suction head will be the same at all points having the same elevation, and between points at different elevations the suction head difference will be equal to the elevation difference.

For the wick case, where water is dripping from the free end, the static relation between suction head and height above the free water surface no longer exists. The wick system now becomes an example of viscous flow in an unsaturated porous medium.

Gravity and the force associated with a pressure gradient are the two forces that determine the flow of water in soil, saturated or unsaturated. Gravity is always present and acts in the downward direction. The pressure force may act in any direction and in magnitude can be expressed relative to gravity, which is 1 g. The pressure force, both in direction and in magnitude, may be expressed in terms of the gradient of the pressure head or suction head. This is the change in head per unit distance through the soil in the direction of the greatest rate of change. The force acts in the direction of the decrease in pressure or the increase in suction and, when expressed relative to gravity, is numerically equal to the change in head per unit distance through the soil.

The condition for static equilibrium is that the pressure gradient force must be equal and opposite to gravity so that the net driving force is zero. In the example of the wick at static equilibrium, the pressure is the same at every point at the same level, so there is no component of the pressure gradient in the horizontal direction. In the vertical direction, below the free water surface, the pressure head increases one unit for each unit of change of distance in the vertical direction.

There exists, therefore, an upward water moving force of 1 g. because of the pressure gradient. Likewise, in the wick above, the free water surface, the suction head increases by one unit for each unit of vertical rise in the wick. Here also there is an upward water moving force of 1 g., which just cancels the effect of gravity. These conditions apply also for water in soil. When the pressure gradient force is equal and opposite to the gravity force, the two driving forces are balanced and the condition is met for static equilibrium.

The combined action of pressure and gravity in determining the flow and distribution of water in soil may be expressed conveniently in terms of the gradient of a combined head, referred to as hydraulic head. This quantity has a value at each point in a connected soil-water system and is useful because it can be conveniently measured under actual working conditions.

Hydraulic head is the elevation at which water stands in a piezometer or manometer tube connected to the point in question in the soil. Like any other elevation, hydraulic head has the dimensions of length and is the vertical distance from a standard datum, which may be arbitrarily selected at convenience. The change in hydraulic head per unit distance through soil indicates the net or combined force action of pressure and gravity in causing motion of water

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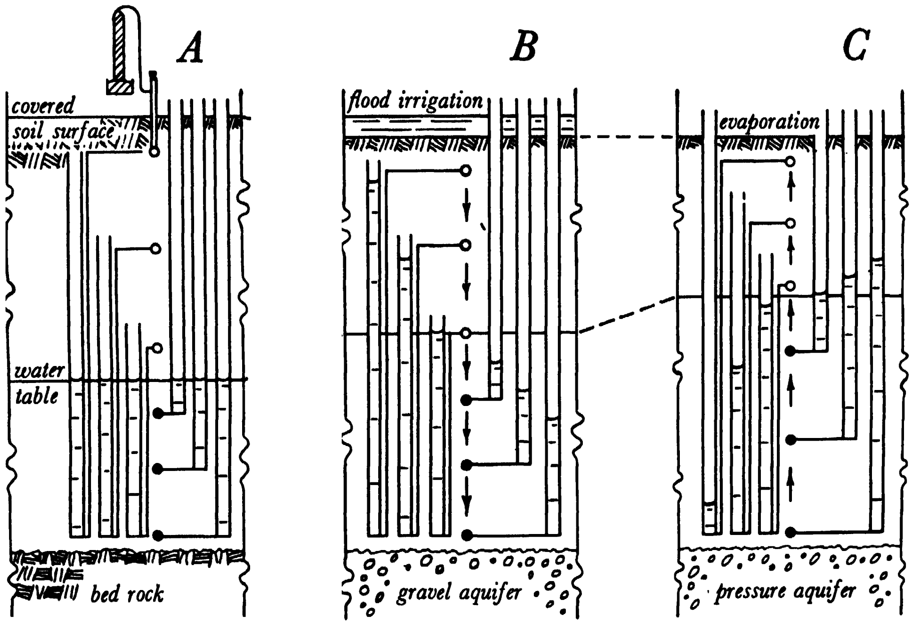


Hydraulic-head relations in three soil profiles, representing A, hydrostatic balance; B, downward flow; C, upward flow.

through soil. Those who have a detailed interest in soil-water relations may find it worth the time to study through the hydraulic conditions illustrated in the accompanying diagram of three soil profiles.

PROFILE A at the left represents static equilibrium in a soil containing a water table. The soil is underlain with an impermeable layer and the surface is protected from evaporation. The open circles represent porous tensiometer cups. The suction head at the porous cup in these units is ordinarily read on a mercury manometer, which is located above ground. One such unit is illustrated at the top of the profile. There is shown, diagrammatically, at the left, a water manometer connected to the same cup. At static equilibrium in this case, as was the case for the wick, the suction head at the cup is the vertical distance down to the water table, which is the level of the water surface in the equivalent water manometer. Suction head at the other two porous cups located in the soil above the water table is likewise indicated. For studying the hydraulics of saturated soil—that is, ground water that is below the water table—small open-ended pipes are inserted in the soil to the depth at which it is desired to read the hydraulic head. These terminal points are represented by the black circles with connecting lines to the corresponding water columns in the piezometer tubes. It is necessary to choose a local reference level for expressing hydraulic head, and in the present example the soil surface will be used as the datum.

Referring to the definition of hydraulic head, it is noted that at the six points on a vertical line, represented by the circles, the hydraulic head is the same at all points. It is equal to the vertical distance from the soil surface down to the water table. It thus appears that the definition for hydraulic head has been chosen so that the con-

dition for static equilibrium is simply given—namely, static equilibrium exists when the hydraulic gradient is zero.

PROFILE B illustrates the downward movement of water under flood irrigation to a water table and thence on downward to a permeable aquifer. Here again the hydraulic head is indicated for six points on a vertical line in the profile. The suction head at the top cup is seen to be small and is equal to the vertical distance from the cup down to the level at which the water stands in the attached manometer. The suction head at the second cup is likewise small and likewise equal to the vertical distance from the second cup down to the elevation at which the water stands in the second manometer. The hydraulic head difference between the two cups, however, is not small and is indicated by the difference in level of the water in the two manometers. This is shown as being equal to the distance between the cups so that the hydraulic gradient is downward and has a numerical value equal to 1. This indicates that on the average between these two points there is an effective driving force on the water equal to 1 g. In other words, in the absence of a suction gradient, gravity alone is acting.

The third porous cup has zero suction head. This is the condition for the water table, and, the water table therefore is drawn as being on the level with the third cup. The first piezometer indicates hydraulic head at the first black circle. Even though this piezometer terminates below the water table, it does not indicate the true location of the water table as in the case for profile A. It is noted that a hydraulic gradient exists in the interval between the water table and the lower end of the first piezometer. The hydraulic head is higher at the water table level than at the lower end of the first piezometer, thus indicating a downward hydraulic gradient and a downward movement of water through the soil. A similar condition is indicated for the soil intervals between the lower successive pairs of piezometers. This illustrates how piezometers terminating below the water table at different depths can indicate hydraulic head and hydraulic gradient conditions and can therefore be used to indicate the direction of movement of ground water.

The third profile C represents the condition where ground water is moving upward from an underlying artesian aquifer containing water under pressure. The condition is fairly common in irrigated valleys and causes troublesome drainage problems. Here it is noted that the suction head is high in the surface soil and the suction gradient is far greater than is necessary to counteract gravity, so that there is a net upward water moving force. The water table evidently lies between the third tensiometer where the suction head is appreciable and the first piezometer where the pressure head is appreciable. It would be difficult from either of these measurements to estimate the exact position of the water table because this will depend upon the nature of the soil. Here the piezometers, which measure hydraulic head at three elevations on a vertical line below the water table, indicate that the hydraulic head decreases in the upper direction. This indicates a net upward water moving force and upward flow.

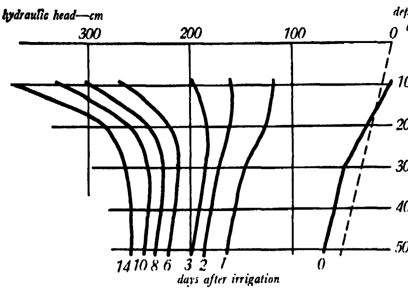
The velocity of movement of water through soil is proportional to the driving force and is expressed by the equation $v=Ki$. The symbol v stands for the volume of water crossing unit area at right angles to the flow in unit time and i represents the hydraulic gradient. The proportionality factor K in this equation is called the hydraulic conductivity. In unsaturated soils, it may be called the capillary conductivity. It has the dimensions of velocity and may be expressed in any convenient velocity unit. Since it is the ratio v/i, it is the calculated value of the flow velocity for a net driving force of 1 g.

Application of these hydraulic principles may be illustrated by measure-

ments taken in a field plot of Pachappa sandy loam soil at the United States Salinity Laboratory. Readings were taken with a multiple-cell tensiometer having cylindrical porous cups mounted in a plastic tube at 10-cm. intervals from 10–50 cm. deep. The instrument was mounted in a single hole made by a soil tube so that the soil profile was substantially undisturbed. The curves show distribution of hydraulic head values with depth following an irrigation on July 24, 1953. The numbers at the bottom of the curves indicate elapsed time in days following irrigation. The soil surface was the reference datum so the hydraulic-head values are negative and are plotted in the third quadrant.

Hydraulic-head values read from the top scale give the depth below the soil surface at which water would stand in an equivalent water manometer connected to the porous cup at the depth indicated on the right-hand scale. The dotted line at the right indicates the slope for unit hydraulic gradient. The curve at zero time indicates the hydraulic-head distribution with depth toward the end of the infiltration period when the rate of entry of the irrigation water as measured in a one-meter cylinder within the three-meter square plot was 2.6 cm. per hour. The curve showing the variation of hydraulic-head values with depth at this time indicates that the hydraulic gradient was constant in the 10–30-cm. depth interval and equal to 2.3. This ratio of $v/i=2.6/2.3$ corresponds to a hydraulic conductivity value of 1.1 cm. per hour. The hydraulic gradient in the 30–50-cm. depth interval was unity indicating downward movement under the action of gravity alone. The average hydraulic conductivity of the soil in this interval was, therefore, $v/i=2.6/1=2.6$ cm. per hour.

By definition, the suction head at any cup at any depth is equal to the hydraulic head at that depth minus the depth of the cup. Graphically the suction at any cup is obtained by subtracting the horizontal distance between the dotted line at the right to the vertical scale at the right from the hydraulic-head value given on the horizontal scale. In the depth interval from 30–50 cm., during the infiltration process, the curve indicates the suction head was constant and equal to 14 cm.



Curves showing changes of hydraulic head with depth and time following basin irrigation for Pachappa fine sandy loam.

The lateral shift of the hydraulic-head curve after one day corresponds to an increase in suction head of about 100 cm. at all depths and is caused by the loss of water from the profile by downward drainage. One day following irrigation the hydraulic gradient is nearly uniform throughout the depth of measurement and equal to 1. The suction gradient is negligible and gravity alone is the driving force.

THE BENDING of the upper ends of the hydraulic-head curves to the left is caused by evaporation of water at the soil surface. By the second day, a maximum point on the hydraulic-head curve indicated by the large circle occurs in the 10–20-cm. soil-depth interval. At the maximum point, the hydraulic gradient is zero. This is the condition for static equilibrium under gravity so this maximum point indicates the presence in the soil of a static zone above which soil water movement is upward and below which soil water movement is downward. The large circles on the subsequent curves indicate the rate of lowering of the static zone through the profile. By the 14th

day, the static zone had passed below the 50-cm. depth.

The pattern of change of the net water moving force in the 10–20-cm. depth interval was as follows. During infiltration, there was a downward water moving force of 2.3 g. Gravity was aided by 1.3 g. of suction force produced by underlying soil. By the second day, the average hydraulic gradient was zero, indicating the suction gradient had reversed and had an upward value of 1 g., thus canceling the downward force of gravity. By the 14th day, there was a net upward water moving force in the 10–20-cm. interval of 8.8 g.

THE SUCTION and suction gradient depend upon the water content of the soil. Three curves are given to illustrate the nature of this dependence. The moisture content is expressed as the depth of water per hundred units of depth of soil. This is numerically equal to the percentage of the soil volume that is occupied by water. The suction is expressed in atmospheres. A suction head of 1,034 cm. corresponds to 1 atmosphere. These retention curves were obtained for soil cores having field structure. The curves shown are moisture release curves since initially the cores were saturated and the moisture content was measured by weighing after the cores had come to hydraulic equilibrium with a control surface composed of a porous ceramic plate or a cellophane membrane.

The curves have considerable theoretical and practicable significance.

The depth percentage at zero suction indicates the total porosity of the soil or the percent of the total soil volume that is made up of connected pore space.

The equivalent pore-size distribution of a soil may be obtained from the moisture retention curve. The suction exerted by a water meniscus in a cylindrical pore is related to the diameter of the pore. The volume of water released by a soil in a given suction interval, therefore, is an index of the total volume of pore space in the equivalent pore-size range corresponding to the suction range. It is seen that for the sandy soil a suction head of about 100 cm. will empty nearly three-fourths of the total pore space, but this suction for the clay soil causes practically no change in water content. This means that, when static equilibrium is approached from the wet side in the clay soil in the field, the clay will remain saturated for 100 cm. above the water table. Moisture release curves, such as those illustrated, give the distribution of water with height when the soils have drained to static equilibrium with a water table.

The low moisture end of the curves is significant because it has been found that the 15-atmosphere percentage corresponds closely to the permanent-wilting percentage. Numerous experiments with plants show that this moisture content is the lower limit of the range of soil moisture that will permit the vegetative growth of plants and this important moisture characteristic of soil appears directly on the retention curve.

The upper limit of the field moisture range in which plants can grow is less definite than the lower limit. Much effort has been spent in search of a satisfactory laboratory procedure for estimating this upper limit, but no measurement that is satisfactory for general application to all kinds of soil has been found.

The water content of a sample of soil that has been air dried, sieved, wetted, and brought to hydraulic equilibrium with a ceramic plate at a suction head of 100 cm. approximates the water content a day or two after wetting in the field for some coarse-textured soils. The curve giving hydraulic-head distribution one day following irrigation of the Pachappa sandy loam, for example, indicates the suction head is nearly uniform with depth and is approximately equal to 100 cm. This relation does not hold, however, for most medium- and fine-textured soils.

The water content to be found in

soils following wetting will depend on the water-retaining and water-transmitting properties of the soil and the hydraulic boundary conditions that determine the hydraulic gradient. The hydraulic head near the surface of the soil will be affected by climate, plant cover, and water extraction by roots. Hydraulic boundary conditions in the wetting front and below will depend upon the initial water content of the soil and its water transmitting properties. Wet subsoil limits the downward suction gradient and slows drainage. Likewise, a restricting layer or an abrupt transition to very coarse texture may act like a water table in their effect on the hydraulic gradient and the downward movement of water. It is difficult in laboratory determinations for indicating the upper limit of the field moisture range to duplicate the hydraulic boundary conditions existing in the field.

The retention curve for the Chino clay soil indicates a moisture content difference of 16 percent, on a volume basis, between saturation and the 15-atmosphere percentage. The available range for plant growth will be less than that. The Pachappa fine sandy loam has an unusually wide available range, approaching 25 percent, but the Hanford sand has an available range of only about 8 percent. This corresponds to 8-cm. depth of free water per 100 cm. of depth of soil like that for which the curve was obtained. Soil is definitely on the marginal side for normal irrigation agriculture if the available range is as low as 8 percent. Frequent irrigation is required to keep crops in good growing condition, and water application must be light to avoid leaching losses of water and nutrients.

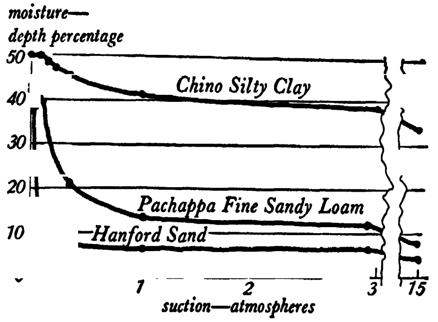
One of the important characteristics enabling soil to store water for plant use is the large decrease in the readiness with which soils transmit water as the soil dries out. This is indicated by the change in the capillary conductivity with increasing tension. This quantity is the proportionality factor in the flow equation $v=Ki$, which was mentioned earlier, and represents the flow velocity at unit hydraulic gradient. For Pachappa fine sandy loam, K is approximately 2 cm./hour at saturation or zero suction head. This reduces to 0.2 cm./hr. at 75 cm., 0.02 cm./hr. at 120 cm. and 0.002 cm./hr. at 200 cm. of suction head.

The volume or depth of water that will return to the surface and be lost by evaporation from fallow soil as indicated by the hydraulic-head curves previously given may be estimated from soluble constituents in the irrigation water. On July 20, 1954, a plot of Pachappa fine sandy loam was irrigated with water containing 44 milliequivalents per liter of potassium chloride. Samples taken the day following irrigation contained about 40 meq/l of chloride in the soil solution, and this was uniform with depth. Samples taken a month later indicated that, on the basis of chloride transfer, 2.9 cm. of water had moved upward into the 0–5 cm. layer of soil. Adding to this 1.4 cm., which represents the net water content loss from the 0–5-cm. layer, gives a value of 4.3 cm. of water for the evaporation loss from the soil surface during the 1-month period following irrigation. This figure is in good agreement with soil moisture content samplings and also with calculations based on capillary conductivity and hydraulic gradient measurements.

This experiment also provided new information on the significance of the water-vapor transfer within this soil profile during a month of hot weather. If water movement within the soil were entirely by liquid or film flow, no change would be expected in the concentration of the soil solution. Evaporation within the profile would cause an increase in concentration, however, and, conversely, condensation within the profile would cause a decrease in the concentration of chloride in the soil solution. From chloride concentration measurements there was no evidence of vapor transfer in the soil profile below the 10-cm. depth.

There also was approximately a 10-

percent decrease in the chloride concentration in the 5–10-cm. soil interval. This could have been caused by condensation of water vapor that diffused downward from the warmer surface soil. The condensate would dilute the soil solution. However, the upward flow of film water in response to the suction gradient dominated the water transport processes in the 5–10-cm. soil interval and was the mechanism responsible for the movement of salt to the surface.



Retention curves showing the change in water content of soil cores as the suction is increased from zero to 15 atmospheres.

The hypothesis that the readiness with which plants can absorb water from soil is measured directly by suction or suction head has evolved over a period of years. The evidence supporting the hypothesis has been reviewed in the monograph of the American Society of Agronomy, *Soil Physical Conditions and Plant Growth*. The usefulness and significance of moisture retention curves as they relate to this hypothesis is at once apparent.

The foregoing discussion in terms of hydraulics has omitted complicating factors, such as capillary hysteresis, temperature, and the effects of soluble and exchangeable ions on the hydraulic properties of soils. For many practical purposes, however, the simplified treatment aids in understanding and quantitatively expressing observed phenomena relating to the retention and transmission of water by soil.

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How Much of the Rain Enters the Soil?

G. W. Musgrave

What really counts in a rain is how much of it enters the soil.

The nature of the soil, its condition, the nature of the storm, and the season of the year determine infiltration, the amount of water taken in by the soil.

Infiltration tends to be higher in the warm months than in the cool months. Wide differences in infiltration occur in row crops, pastures, and hayfields.

On the Middle Branch of Westfield River at Goss Heights, Mass., the average annual amount of intake is 19.6 inches—or about 43 percent of the annual rainfall. On the Red River at Fargo, N. Dak., it is 19.7 inches—or about 94 percent of the annual rainfall. On the Pearl River at Edinburg, Miss., it is nearly twice as much, 38.8 inches, which is about 70 percent of the rainfall. In some parts of the Southwest the annual runoff averages less than 0.01 inch, but there the rainfall is also low. Those results are from relatively large watersheds, which have different soils and vegetation.

It is not easy to measure infiltration accurately. Several methods are available, but some are not entirely reliable. On large watersheds it is customary to take the difference between rainfall and runoff as an index of intake. But that is not strictly accurate, because

such calculations include the amount of rainfall that wets the vegetation and the ground surface and fills the many small depressions found in any locality. Near the end of a big storm, however, after the depressions have been filled and the entire area has been soaked, the difference between rainfall and runoff closely represents intake.

In places where rates of rainfall and rates of runoff are measured, we can determine the rate of infiltration.

Storms suited to such measurement are uncommon; most storms have high and low intensities of rainfall at different times and in different places on large watersheds. This method is not well adapted to a comparison of soils and vegetation, because most watersheds have more than one kind of soil and vegetation. Unless several recording gages are used on the watershed, the true amount of rain falling on each part is not known.

To overcome some of the difficulties, equipment has been designed that will provide artificial rainfall, uniform in rate and of large amount (since the amount must really test the capacity of the soil). The equipment can be moved from one soil or kind of vegetation to another and thus sample different conditions within a watershed.

Most commonly used is the Type F infiltrometer. A smaller version, the Type FA infiltrometer, is especially useful in localities to which it is difficult to transport the large quantities of water required by the Type F. Both provide raindrops large enough to approximate the surface impact of natural rain. The rainfall is applied at a known rate, and the rate of runoff is measured. From these the rate of intake is calculated.

Water is applied to two of the commonly used types of infiltrometer (tubes and concentric rings) by flooding the soil surface without greatly disturbing the soil structure. The flooding types give consistently higher infiltration than the rainfall types, but the differences are less under dense vegetation than under sparse vegetation.

The different types of infiltrometers are useful in determining the relative differences between the intake of different soils and vegetation. Intake rates often must be learned for areas where facilities for making measurements differ widely. In places where water supplies are limited, one of the smaller infiltrometers, which require a small amount of water, is ordinarily selected. If better quantitative data are needed and facilities permit, the large Type F infiltrometer is ordinarily used.

Comparisons of different types of equipment operated side by side have shown that relative comparisons of soils and vegetation can be obtained from any of them. The comparisons also show that the intake rates are higher from types that apply water by flooding than from types that apply water as artificial rainfall. But they also show that no simple relation exists between the results of different types applied to different soils or vegetation and that no easy way exists of converting the results from one type to equivalent values of another type. Clearly the nature of soil or vegetation is reflected to divergent degrees in the different techniques used for the measurement of intake. That is not surprising, because the full protective effect of vegetation found under rainfall cannot be measured when water is applied by flooding. Yet all of these methods have a place in the evaluation of the factors that affect intake and also in the evaluation of the different parts of a watershed.

Relative values of intake on a watershed are best obtained from the watershed itself. On watersheds for which we have good records of rates of rainfall and rates of runoff, a comparison, storm by storm and hour by hour, gives us results that reflect the rates of intake when wet or dry, the change with season, or the drop toward the end of storms. These intake rates for the watershed also are weighted by the proportions of soils and vegetation occurring in the area. A number of years of records are needed for such deter-

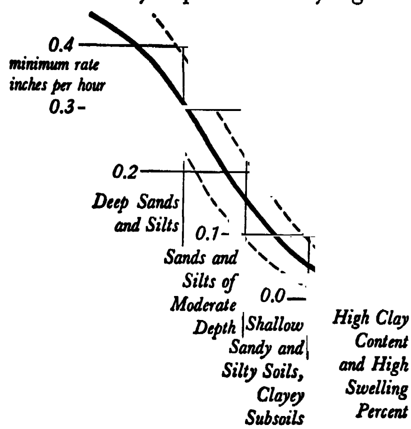
minations so that large storms are included and the effect of seasons and moisture conditions are represented in the records.

Watersheds that do not have records of rates of rainfall and runoff but have only storm totals can be used to determine approximate rates of intake. The difference between total rainfall and runoff, while including some other items, is mostly infiltration. With a large number of records, the average may be estimated as the difference between rainfall and runoff divided by time. Such records are often available, whereas records including rates are seldom available. Average intake rates derived from total rainfall and runoff thus can serve a useful purpose in watershed evaluations.

On the many watersheds for which such records are seldom available, it is possible to map the soils and kinds of vegetation. The infiltration for different soils having various kinds of cover—that is, a soil-cover complex—may be estimated for each combination. Each of the estimates for the areas in the watershed may then be used to calculate "rainfall excess," and those calculations in turn may be combined to estimate the runoff from the entire watershed. The estimates of runoff may be compared with recorded events, and discrepancies in the estimate of infiltration for certain soil-cover complexes can be readjusted so that the actual observed amounts and the computed amounts agree. The estimates of infiltration may then be applied to the watershed having the changed surface condition. Thus we can assess the improved runoff conditions and the amount of reduction in damage therefrom.

On watersheds where no rainfall and runoff information is available, it is necessary sometimes to estimate the rate and amount of infiltration from other sources. A guide for doing so is outlined here.

A given soil-cover complex, when thoroughly wetted by prior rains, has a minimum rate of intake that is reasonably constant and reproducible for this condition. Such minimum rates obtained for row crops during the warm months have been determined for many soils and are usable—with other data—in placing the soil-cover complexes in relative order within the continuous array represented by figure 1.



The range of minimum infiltration rates with row crops on wet soils. The variation due to past treatment is shown by the dashed line about the mean.

The chart represents the range for the important soil groups, each with minimum cover and thorough prior wetting, and after a long rain in excess of the infiltration rate. They are thus minimum rates, typical of the growing season of the region. They do not show what happens when the ground is frozen. The broken lines on each side of the curve represent the normal range for the soil-cover complex, which necessarily varies with soil depth, past history of tillage and cropping, and content of organic matter.

THIS ARRAY of soil-cover complexes may be divided into four infiltration groups.

Group A includes the very permeable deep sands and deep aggregated silts of loessial origin; they have little clay and colloid, and the silts have enough organic matter to provide good aggregation.

Group B includes sandy soils and silt loams of moderate depth and above-

average infiltration; the minimum figures for it range from about 0.15 to 0.30 inch an hour.

Group C includes shallow soils in all textural classes; their minimum infiltration rates are below average (0.05 to 0.15 inch an hour).

Group D includes soils with high swelling rates in the surface or subsurface because of high content of clay or colloid; its minimum infiltration rates approximate 0.05 inch an hour.

Each group contains individual units (soil-cover complexes) whose rate of infiltration has been measured by one or more methods. The position of the curve has been determined by minimum rates found on large watersheds. The relative position of the units on the curve has been determined on a comparative basis, for which all available data were considered.

Examples of soils in these soil-cover complexes are given in the table. Since such specific information is not recorded for all soils, the list provides a guide and base points into which other soils may be inserted. Given the texture, soil depth, and other characteristics of soils M and N, a technician ascertains the similar characteristics of soil X and then, through interpolation, can properly place the unknown infiltration of soil X in the list of known soils.

Studies of the physical characteristics of soil show that infiltration in surface soils is correlated positively with its content of organic matter, state of aggregation, and amount of large pores, but negatively with the dispersion of particles. In the subsoil it is also correlated positively with content of organic matter and the amount of large pores and negatively with amount of clay and density of the soil horizon.

THE SOIL CHARACTERISTICS that govern infiltration, to repeat, include the primarily physical properties like texture and depth to the slowly permeable horizons. One also has to take into account the prior history of tillage, which strongly affects structure, or the arrangement of soil particles.

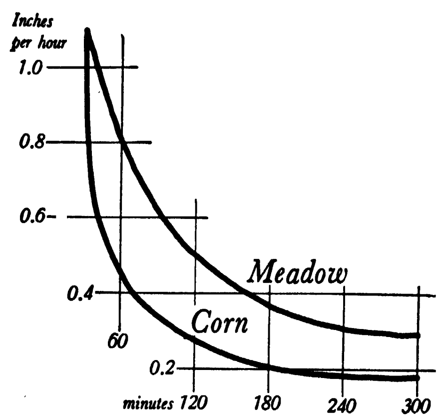
Some of our highest rates of infiltration occur on deep silt loams that are highly aggregated and therefore have relatively large pores. Sometimes the aggregates are the size of coarse grains of sand, and the infiltration is like that of coarse sand as long as the structure is aggregated.

Many hazards beset that favorable structure. One of the most common factors is intensive tillage, which breaks up the aggregated soil particles and exhausts organic matter, one of the essentials of aggregate formation.

Rain on bare soil also breaks up soil aggregates, leaving a compact, dense surface layer, through which water can move but slowly. Grass, trees, or straw mulches protect soils from such forces of disintegration and are also sources of organic matter useful in the renewal of good soil structure.

Beneath intertilled crops like corn, cotton, peanuts, potatoes, or soybeans, infiltration is usually much less than beneath grass, trees, or mulches. The gain in infiltration resulting from a change in vegetation is greater quantitatively on deep, permeable soils than on shallow, tight ones. The potentialities for practical improvement are less on the latter.

The data in the second figure were



A comparison of infiltration under bluegrass pasture and under corn, showing the more rapid decline in rate for the row crop.

obtained by sampling fields in Illinois where the grass was being grazed and the corn was handled as in normal farm operations. Large and consistent differences occur in the infiltration under corn and under grass. The differences are consistently greater on the deeper soils. Not brought out in the figure itself is the fact that fields that had been in grass for 20 or more years had higher infiltration than fields in grass for 10 to 20 years. The latter, in turn, were higher in infiltration than those that had been in grass 5 years. Clearly the number of years affected the rate; that could come only from residual effects associated with aggregate formation, including primarily an accumulation of organic matter beneath the sod.

Crop rotations are intermediate between grass and corn in effect. The more sod-formers in the rotation, the greater the effect on infiltration—corn, grain, and hay (1 year each) do not affect infiltration so much as does a 4-year rotation of corn, grain, and hay. Small grain also is intermediate between row crops and grass in its effect. Intertilled orchards have a lower infiltration than do orchards in sod.

In estimating infiltration for soils varying from average condition, some further principles should be recognized.

1. Differences in infiltration for different soils are correlated especially well with particle size, amount of organic matter in the soil, and soil depth. These are the main characteristics of a soil to examine in estimating the infiltration.

2. Differences in infiltration for various crops are smaller (*a*) when the soils approach saturation; (*b*) when the soils (if they contain considerable clay or colloids) are in their maximum swollen condition; (*c*) in the cool months rather than the warm months.

3. Different soils must be judged on the basis of their individual physical properties:

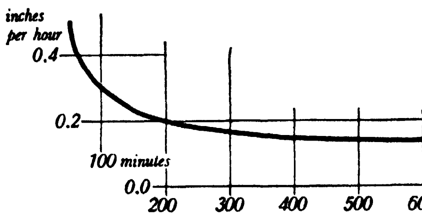
(*a*) Clay soils with a high degree of swelling when wet can be expected to have a much lower rate of intake in this condition than when dry. If cracking is common and extensive when dry, the rate of intake then may be relatively high. (Houston clay is an example.)

(*b*) Deep sands or soils low in clay and colloid may have rather high rates even when near saturation because swelling is not appreciable. (A deep Norfolk sand is an example.)

(*c*) Lateritic soils or those from which the colloids have been leached to some extent also tend to retain their initial intake rates after wetting. (The Cecil soils of the Southeastern States, for example, show a relatively slow decline in rate as wetness is increased.)

(*d*) Soils with water-stable aggregates do not decline in rate so rapidly as those whose aggregated structure is less stable. Silt loams high in organic matter and those of fairly high pH often fall in this class. (An example is the Honeoye series in parts of New York.)

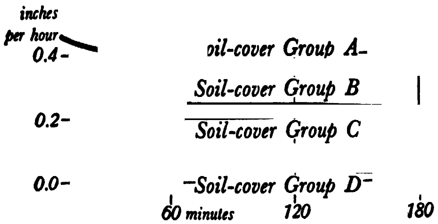
Those relationships govern in principle the shape of the infiltration curve as it declines with time. In figure 3 the decline in rate for a soil in the C hydrologic group is shown for the average moisture and other surface conditions during 149 storms. At 10 hours after start it drops to a near-constant rate of 0.15 inch an hour.



Infiltration under average soil moisture and temperature during 149 storms—row crop, C soil group. (A list of soil groups is given on page 157.)

A second storm on the same soil is charted in figure 4—the intake now, when the soil is thoroughly wet, declines slowly to about 0.10 inch an hour. Typically, the average curve (as in this example) declines rapidly until it becomes nearly asymptotic,

but some further decline occurs in the storm immediately following.



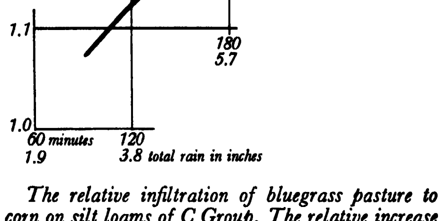
Second storms on wet soils of the groups in the first chart. Compare C Group with its average rate shown in the third chart.

The gain in infiltration that follows a change in vegetation from sparse (as in a row crop such as corn) to dense (as in bluegrass pasture) is shown in figure 5, which is representative of the C hydrologic group. The relative gain is not so great as in that of the B group, where the soil depth may be greater. The gain in sands may be less because no great degree of aggregation follows from the growing of grass. Lateritic soils (such as the Cecil) also may show gains less than that in figure 5, although more than in sands. In the tight clays of the D infiltration group, no large gain occurs from improved vegetation when these soils are swollen and saturated. A factor that affects the amount of gain from grass in the A, B, and C groups (where aggregation is possible) is the age of the sod. Significant positive correlations for 5-, 10-, 15-, and 25-year-old sod indicate that aggregation progressed as organic matter accumulated and as the other processes favoring the formation of large pores had time to become effective.

An effective way to increase infiltration is to use a mulch of straw, crop residues, or other plant materials. At Zanesville, Ohio, an extensive series of experiments were made with different kinds of pretreatment and different kinds and rates of application of mulch. The results showed that the function of the mulch is primarily to protect the existing favorable structure. If the soil is not permeable, the mulch does not make it so. When a tight soil was cultivated one inch deep and as little as two tons an acre of straw applied to the surface, however, the infiltration rate after 60 minutes of rain was 2.10 inches an hour, and 1.63 inches an hour 100 minutes after the rain started. On land without mulch but otherwise similar in all respects, the rate of infiltration dropped to 0.28 inch an hour within 60 minutes after the start of the rain. The impact of the rain on the unprotected soil produced the typical dense soil surface, which at best is only slowly permeable.

Even stones on the surface may provide some protection. Two plots of Bath flaggy silt loam near Ithaca, N. Y., had a natural cover of small, flat stones. After the stones from one plot were removed, its infiltration dropped greatly below that of the other with its natural stone mulch.

Crop residues of many kinds are used. Tillage practices are being improved so that the subsurface may be broken and a protecting mulch of vegetation left upon the surface. Horticulturists, highway officials, and others sometimes use a burlap cover on steep, newly seeded slopes. Such practices permit improved infiltration, reduce



The relative infiltration of bluegrass pasture to corn on silt loams of C Group. The relative increase on deep silts may be greater than that shown; the relative increase on sands may be less. Lateritic soils may also be less than that shown by the curve, although greater than for sands.

soil temperatures, and maintain soil moisture at the surface, where germinating seeds can become established.

Fields repeatedly in wheat were investigated at Hays, Kans., and comparisons made between plots on which the stubble was burned before seeding and plots where preseeding tillage was such as to leave the stubble on the surface. The total amount of infiltration during a storm was 0.71 inch where stubble was burned and 1.16 inches where its protecting influence remained at the surface.

The effect of temperature on the rate of infiltration is shown in figure 6, which records a 72-hour test in which soil and water temperatures fluctuated daily more than 20° F., reaching daily the maximum at about 1 p. m. and the minimum at about 6 a. m. The oscillating infiltration curve, if computed

Tentative Array of Soils in order of Minimum Infiltration Rate (Preliminary Grouping)[1]

D—Lowest Group

(Minimum infiltration rate: 0 to 0.05 inch an hour)

Includes soils of high swelling percent, heavy plastic clays, and certain saline soils.

Examples (from low to high):

Houston
Austin
Trinity
Susquehanna
Lufkin
Some gumbos

C—Below Average Group

(Minimum infiltration rate: 0.05 to 0.15 inch an hour)

Includes many clay loams, shallow sandy loams, soils low in organic matter, and soils usually high in clay.

Examples (from low to high):

Bellmont	Berwick	Bates
Bluford	Bogota	Shelby
Cisne	Del Rey	Iredell
Eylar	Atterbury	Elkton
Jacob	Batavia	Vernon
Okaw	Clarksdale	Cecil clay loam
Racoon	Elliott	Dunkirk
Rushville	Shiloh	Miami
Weir	Upshur	Fillmore
Breese	Putnam	Butler
Cowden	Muskingum	Kirkland
Ebbert	Westmoreland	Rosebud
Clarence	Parsons	Myatt
Patton	Volusia	Kalmia
Rantoul	Viola	Appling
Swygert	Crown heavy clay	Seneca
Wabash		
Ava		

B—Above-Average Group

(Minimum infiltration rate: 0.15 to 0.30 inch an hour)

Includes shallow loess and sandy loams.

Examples (from low to high):

Arenzville	Melbourne	Tama
Camden	Sylvan-Blair	Orangeburg
Youthful Ava	Athena	Carrington
Walla Walla	Davidson	Hopi
Sharpsburg	Monona-Marshall	Ruston
Selah	Ida	Aiken
Buell	Tama	Hagerstown
Badger	Marshall	Hamburg
Clinton	Fremont	Muscatine
Colby	Webster-Clarion	Saybrook
Greenville	Fayette	Harpster
Boone	Seaton	Ellison
Red Bay	Sylvan	Kincaid
Cecil fine sandy loam	Flanagan	Waukesha
Palouse	Huntsville	Judson
Dubuque		Honeoye
Kirkland		Madison
		Durham

A—Highest Group

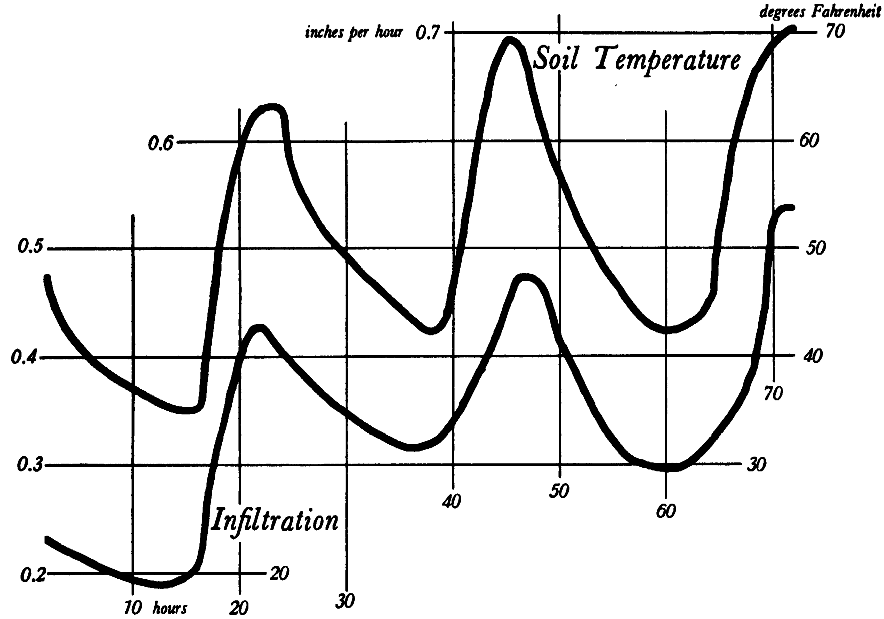
(Minimum infiltration rate: 0.30 to 0.45 inch an hour)

Includes deep sand, deep loess, aggregated silts

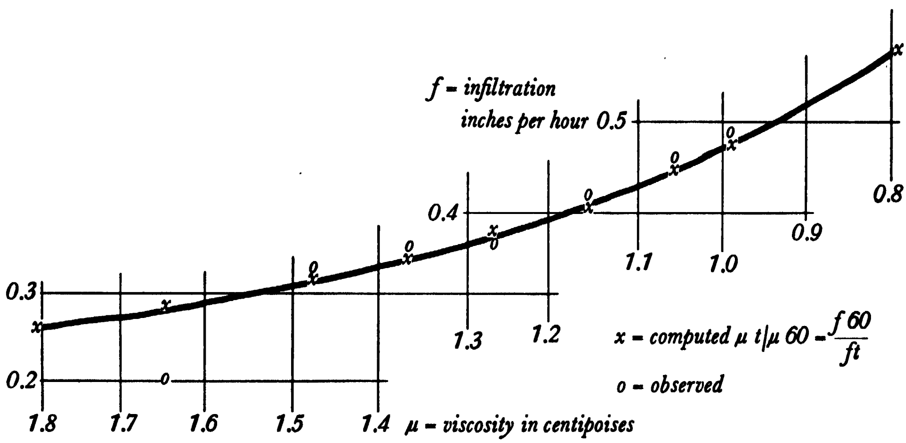
Examples (from low to high):

Knox
Other deep loess
Nebraska Sandhills
Southeast Sandhills

[1] The soils listed have had some measurements of infiltration upon which the tentative array herein is based. It is recognized that some shifting of order is still necessary. Other soils may be added on the basis of the judgment of soils technicians. The names of some of the soils have been changed through recorrelation. The entire list therefore is tentative.



Temperature and infiltration in 72-hour continuous test near Colorado Springs, where infiltration is proportional to viscosity of water.



Viscosity of water and rate of infiltration, Colorado Springs, Colorado.

to a constant temperature and viscosity of water, becomes the curve of figure 7, which shows that there is nearly perfect correlation between infiltration and viscosity of water. (A common example of the effect of temperature and viscosity is the flow of molasses, which is much slower when cold than when warm.)

So, in summary, the major factors that affect intake of water by soil are—

(1) surface condition and amount of protection against the impact of rain;

(2) internal characteristics of the soil mass, including pore size, depth or thickness of the permeable portion, degree of swelling of clay and colloids, content of organic matter, and degree of aggregation;

(3) the moisture content and degree of saturation;

(4) the duration of rainfall or application of water;

(5) the season of the year and temperature of soil and water.

Of the five, the ones readily modified by man's action are those dealing with the surface condition of land and its protection against rain impact. Protective covers of vegetation or mulch, with the consequent accumulation of organic matter in the soil, do essentially what Nature has done throughout the centuries. By intensive tillage man disposes of or obliterates the vegetation that provides surface protection and accelerates the loss of organic matter. By crop rotations that include grass and legumes, by continuous or long-time grass crops, and by providing a mulch, he recovers a part of the loss he has caused. Infiltration is improved but not to its full former rate.

For further improvement in intake he looks largely to mechanical means, including terracing, contouring, and various means of retarding surface flow and thus providing more time for the intake of water.

It has been argued that the increased infiltration due to conservation treatment may appear downstream as surface runoff and that this increase may add to the peak discharge. Such a chance exists, but it is obvious that the movement of water through the soil mantle is slower than its movement across the land surface. The probability that this outflow will be timed perfectly to coincide with the peak discharge of surface flow is quite remote.

Most plantlife is dependent upon the intake of water by soil. Springs, wells, ground-water supplies, and the base flow of streams are dependent on it. To no small degree, man's use and management of the land govern the rate and amount of intake. Fortunately, wise management of land, so that the natural structure of soil is preserved or restored in some measure, is normally beneficial to crop and livestock production, and in addition provides a practical means of supplementing mechanical measures for the reduction of excessive runoff.

G. W. MUSGRAVE *has devoted a large part of his time since 1929 to problems relating to intake of water by soil. As superintendent of the Soil Conservation Experiment Station at Temple, Tex., and later at Clarinda, Iowa, and Bethany, Mo., his attention was directed toward the rainfall that does not run off the land. More recently he has been research specialist dealing with infiltration, and is now staff specialist in the Engineering Division of the Soil Conservation Service.*

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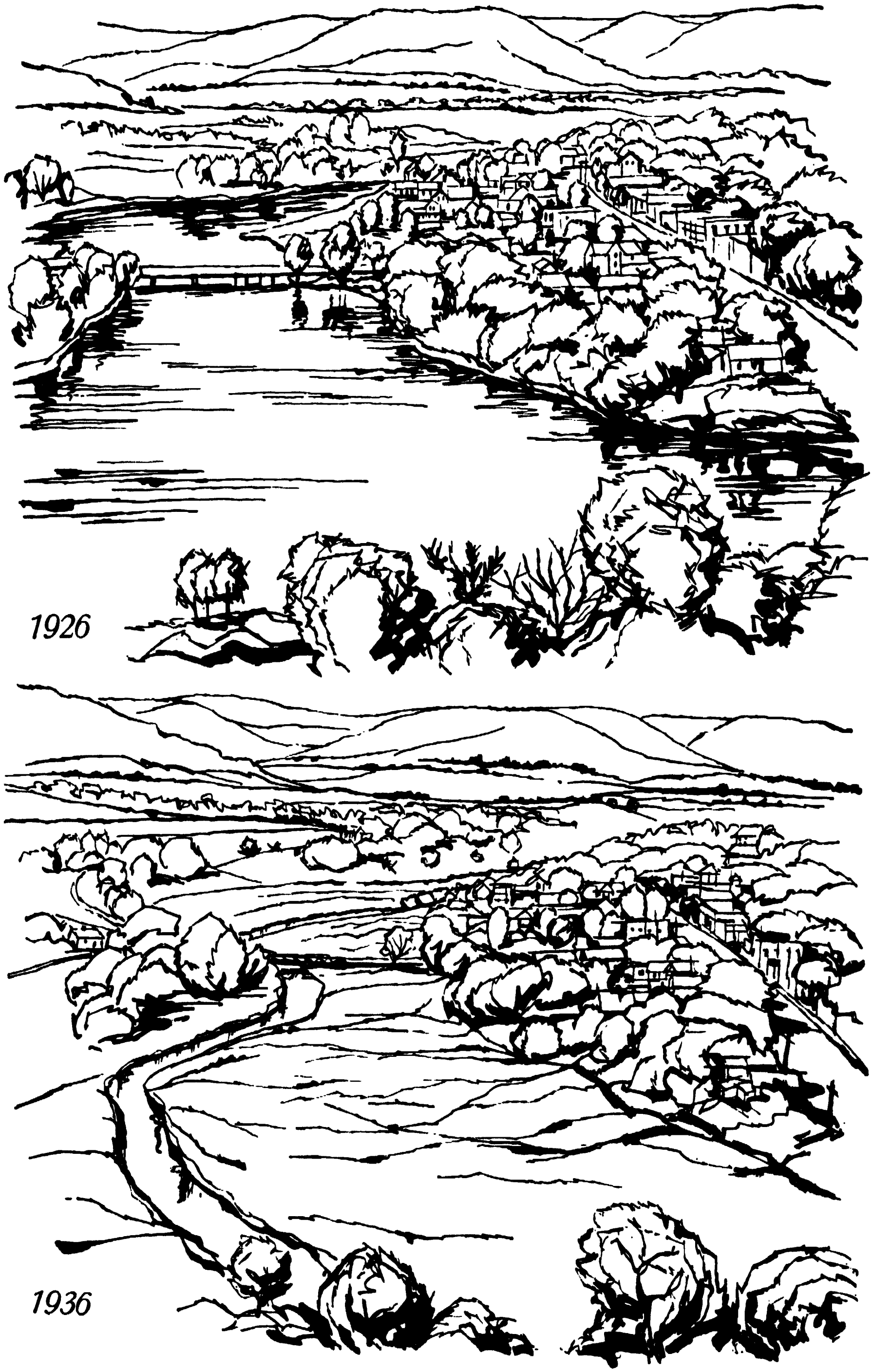
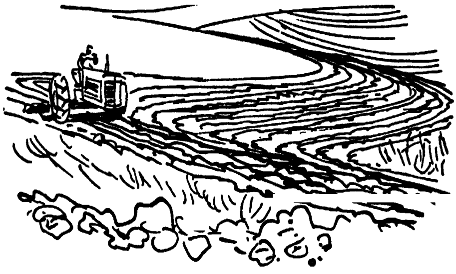


These pictures, drawn from photographs, show Lake Como, Hokah, Minn., 4 years after it had been formed by a new dam, and 10 years later, when it had been silted up.

Caring for Our Watersheds



Conservation Begins on the Watersheds

Carl B. Brown and Warren T. Murphy

A watershed literally is not what it once was.

Thirty years ago that word was almost always taken to mean primarily the drainage divide that separated the waters flowing into different rivers or oceans. Thus the Continental Divide in Wyoming or New Mexico was truly a watershed. Gradually the term "watershed area" came into use to mean the drainage basin of a river or stream. In time the word "area" was dropped, and to most people watershed meant the same as drainage basin.

The transition in meaning is still under way. Scientists or the lexicographers may write about the Missouri, Ohio, or Columbia drainage areas as watersheds, but many persons are coming to think of watersheds as smaller drainage areas. The larger drainages are more commonly called river basins. Very small watersheds—a few hundred to a few thousand acres—are termed subwatersheds.

Watershed now implies a drainage area containing a few thousand or a few hundred thousand acres, from which water drains toward a single channel. It is a social and economic unit for community development and conservation of water, soil, forests, and related resources.

Conservation based on management of watersheds goes far back.

In 1867 a commission was established by the Wisconsin State Legislature. The commission pointed out the relationship between forest cover and streamflow.

A New York State Commission in 1872 investigated the desirability of maintaining the forests of the Adirondack Mountains for the purpose of benefiting the Hudson and other rivers and the Erie Canal.

The American Association for the Advancement of Science sent to the Congress and to the State legislatures in 1874 a memorial, which directed attention to "the drying up of rivulets . . . and the growing tendency to floods and drought."

The American Forestry Congress in 1886 adopted a resolution directing attention to the value of public lands at the sources of streams in the preservation of water supplies and urging that those lands be kept for public use "with a view to maintaining and preserving a full supply of water in all rivers and streams."

In 1891 the first forest reserves were set aside under authority granted by the Congress. In 1897 the Congress, in enacting the Organic Administration Act for national forests, established as one of the principal purposes of such forests the "securing of favorable conditions of water flows."

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During the first 30 years of this century, increasing public interest in waterflow-watershed relationships was reflected in the Reclamation Act of 1902; the establishment of the Forest Service in its present form in 1905; the White House Conference of Governors on the Conservation of Natural Resources in 1908; the Weeks Law of 1911, which authorized Federal acquisition of watershed lands in the headwaters of navigable streams for the purpose of "conserving the navigability of navigable rivers"; the Federal Waterpower Act of 1920; the Flood Control Act of 1927; the McSweeney-McNary Forest Research Act of 1927; and the first Federal appropriation for research on soil conservation in 1928.

During the middle 1930's a series of Federal and State laws were designed to provide the administrative tools and funds for the nationwide effort to develop, improve, and conserve land and water. Noteworthy among many steps taken then were the creation of a Federal agency to combat soil erosion in 1933 and its establishment as the Soil Conservation Service by Act of Congress in 1935; creation of the Tennessee Valley Authority in 1933 to develop an integrated river basin resource development program; enactment of the Flood Control Act of 1936, which recognized watershed treatment as the counterpart and complement of downstream flood control; amendment of the Soil Conservation Act in 1937 to provide incentive payments for soil conservation practices; and enactment by all the States and Territories within a few years after 1937 of enabling legislation for soil conservation districts.

Many constructive forward steps were taken in the decade before the Second World War. Many of them strengthened the Nation's effort in providing more food, more power, better transport, and a greater protection against flood and drought.

But in the postwar era, changing needs, increased public understanding, a different economic climate, and 20 years of experience dictated a reshaping of the public and private approach to many aspects of the development and conservation of resources. In the stream of progress during the postwar years, several developments and trends have been noteworthy.

There is a growing movement away from single-purpose development or conservation and toward integrated or multiple-purpose undertakings. We have learned that the manner in which one resource, such as soil, is handled may have a serious impact upon another resource, such as the water supply or hydroelectric power.

The primary interest was first directed (from about 1933 to 1952) to planning for the resources of major river basins such as the Missouri, Columbia, and Arkansas Basins. As public perspective broadened, it became increasingly apparent that the large river basin is a suitable planning unit primarily for major interrelated projects, such as mainstream navigation and the multiple-purpose dams for power, flood control, and irrigation. Although major river basin programs have set forth desirable broad goals of resource use and have outlined the general relationship between soil and water resources and the major structural projects, they could not get into the details of accomplishing the goals on thousands of individual farms, ranches, and forest holdings. To do that required the understanding and active support of many thousands of individual landowners.

Recognition of this situation has led to the small-watershed approach to the use and development of soil and water resources. The large river basins contain as many as 16 thousand small watersheds, in which there is an existing or potential community of interest among the residents. A small watershed may sometimes be less than a thousand acres and sometimes more than a million acres, depending on the local situation. In the sparsely settled Western States it may be quite large; in the East, quite small. Regardless of

the size, it must be a watershed in which the residents of the area have a sense of common interest and mutual concern.

RECOGNITION of the small watershed as the primary unit of resource development, management, and conservation having to do with water, soil, and related resources is reflected by the formation since 1945 of nearly a thousand watershed groups, associations, and legal organizations. Nearly every important national organization in the fields of industry, labor, agriculture, and conservation has endorsed or sponsored the local-State-Federal partnership approach to planning and carrying out programs within the framework of natural watershed units.

The proportional share of Federal and State interest in the units in relation to the local interest varies from watershed to watershed in accordance with a number of factors, such as the amount of benefits to be derived downstream from the watershed improvement program, the area of Federal and State lands within the watershed, and the relationship of measures proposed in the watershed to overall National and State resource policies and goals. In other words, while the small-watershed approach provides an excellent means for the individual landowner and the local community to participate in the resource improvement program, it is not contemplated that this approach will set up a group of unrelated and uncoordinated programs. Just as the small watershed is a part of a larger watershed unit from which it cannot be disassociated, so are the local communities in the watershed a part of their respective States and of the Nation.

While improvement programs on small watersheds do not lend themselves to building major works, such as hydroelectric power projects, large dams and levees, or primary reclamation projects, they provide a degree of protection against floods, control of erosion, and reduction of sediment that benefits the land of the upper watershed areas. They also contribute to the length of life and effectiveness of the downstream improvements.

The widespread public interest in upstream watershed protection reflects the fact that the national programs of assistance to individual landowners and operators do not provide adequate aid in the solution of the interrelated community problems. Such problems include local agricultural and urban flood control, mutual irrigation developments, drainage improvements on creeks, local water supplies, pollution abatement on tributary streams, improvement of wildlife habitats, and stabilization of large tracts of eroded and gullied lands. In other instances, the application of the general national programs has not gone forward fast enough to solve pressing needs relating to the conservation of water and soil.

To an important extent the widening gap between water needs and water supply has heightened nationwide interest in legislation and in the development of more active programs. In 1955 moves were under way in at least half the States looking toward improved legislation to define property rights in water or to establish enabling or administrative machinery to equip the State and local subdivisions of government to carry out water and land-resources programs.

The 83d Congress added significant new general legislation. We consider three acts especially significant. The first is the Watershed Protection and Flood Prevention Act, Public Law 566. The second is Public Law 597, which amended the provisions of the Water Facilities Act of 1937 by extending its applicability to the entire United States and including within its scope all soil- and water-conserving measures. The third is Section 175 of Public Law 591, Internal Revenue Code of 1954.

Under Section 175, many expenditures incurred for soil and water conservation, which formerly had to be capitalized, may now be treated as expense and will be allowed as deductions from gross income.

The new legislation did not supplant previous legislation, except to the extent that it modified the authority of the Department of Agriculture to participate in programs under the Flood Control Act of 1936. Rather, it supplemented existing legislation and closed gaps not filled by previously authorized programs dealing with the conservation, improvement, and development of soil, water, wildlife, range, and forest. On watersheds, including National Forest areas, it provided a means whereby local interests and individual landowners could cooperate with the Forest Service, the Soil Conservation Service, and State agencies in improving watersheds and preventing flood damages through a coordinated approach including ownerships of land.

The provisions of the Watershed Protection and Flood Prevention Act reflect the new trends in public opinion. More details about it are given in the chapter that follows.

In the broader river basin phases of water resource development, the States are continuing to cooperate with one another and with the Federal Government through interstate compact commissions and interagency river basin committees. Programs and objectives for complete river systems will continue to be developed for those aspects of resource development to which they are applicable. The small watershed program will serve to provide a firmer foundation to the broader programs and help to bring about a realization of broader goals.

INTERESTED persons might ask: What steps can be taken and what kinds of help are available to communities in the development, better use, management, and conservation of land and water in small watersheds?

Individual landowners and operators can take advantage of many forms of public assistance. In every agricultural county in the United States there is a county agent. An employee of the cooperative Federal-State Extension Service, he will, on request, guide the farmer or rancher to the kind of assistance that meets the individual needs of each.

Four out of five farms and ranches in the United States are in soil conservation districts, locally organized and locally managed subdivisions of the States. Their primary purpose is to assist farmers and ranchers in planning and applying measures to conserve soil and water. They are assisted by technical specialists of the Department of Agriculture.

Landowners and operators can obtain financial assistance in varying amounts up to 50 percent of the cost of applying soil and water conservation practices through the Agricultural Conservation Program Service. The program is administered through the County Agricultural Stabilization and Conservation Committees, which are in all agricultural counties.

A landowner can obtain long-term, low-interest loans from (or guaranteed by) the Farmers Home Administration for his out-of-pocket costs for soil and water conservation and water facilities.

Under the provisions of the Internal Revenue Code, landowners can make certain deductions as operating expenses from their gross income for applying many of those measures.

Most of the States maintain forestry organizations. Information regarding tree planting and forestry problems may be obtained from the State foresters or the State extension foresters. In many counties farm foresters, employed by the States, are available to give advice and assistance.

Thus the landowner and operator is given many types of aid and many incentives for conserving land and water—technical help in planning and application of measures, reimbursement for part of the cost of application, access to favorable credit for the rest of the cost, and some opportunities to deduct part of the cost from income tax.

But landowners face problems that they cannot solve individually on their own farms. Also, individuals who are not farmers often have a stake in what

the farmers and ranchers do with soil and water. For example, the farmer himself cannot usually control flooding on his bottomlands because the water comes from a dozen or a hundred farms upstream. Often he cannot drain his lowland because a ditch running through a score of farms must be opened up. Or he needs a better water supply for irrigation and must join his neighbors to develop facilities.

Group action is commonly started by a few community leaders who join to get a job done. This has been the genesis of most of the hundreds of watershed associations formed since 1945. The associations are mainly educational and promotional organizations, dedicated to informing the public about watershed problems and solutions. Some associations have been formed within the framework of existing local organizations, such as soil conservation districts. Others have sprung up independently and proceeded to enlist the aid of all kinds of local groups in a common front.

Once a broad base of public understanding and support has been created among all elements of the community, the time has come for organized action. If the watershed is within the boundaries of a local organization that has authority under State law to carry out, operate, and maintain the needed works of improvement, that organization can seek Federal assistance. Under the provisions of the Watershed Protection and Flood Prevention Act, requests for assistance will be directed to the Department of Agriculture.

More details on how small watershed programs may be developed and carried out by local communities through their local organizations with State and Federal assistance can be had from the State conservationist in each State.

The concept of the small watershed approach to land and water resource development and conservation is just beginning to be effectively applied on the ground. Those familiar with the need for the rehabilitation and better use of the resources believe that this approach will result in definite benefit to the resources, to the citizens of the watersheds, and to the Nation.

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A Law That Puts Responsibility at Home

Harry A. Steele and Kirk M. Sandals

In passing the Watershed Protection and Flood Prevention Act, the 83d Congress emphasized local responsibility in the development of resources.

The act grew out of years of study by the Senate Committee on Agriculture and Forestry, the House Agriculture Committee, and the Department of Agriculture. The study pointed to a need for a national watershed program and disclosed a public demand for it.

The House Agriculture Committee conducted hearings in August 1950 on the proposed agricultural program for the Missouri Basin (H. Doc. 373, 81st Cong.). The program, proposed in 1949, outlined for the first time the size of the watershed protection job for a major river basin. It suggested that the task be undertaken by starting in the places where the problems were most critical and the people were eager to cooperate in solving them.

Two events, which strongly influ-

enced national policy, occurred. Floods, which caused serious damage and took many lives, struck eastern Nebraska in 1949 and 1950. A sequel was the formation of the Salt Wahoo Watershed Association, which was a leader among watershed associations in formulating a watershed program. A severe flood in July 1951 in the Kansas River Basin focused national attention on efforts to prevent floods in the area. Several congressional inquiries and the creation of the Missouri Basin Survey Commission followed.

Hearings held by the House Agriculture Committee in the Midwest in the fall of 1951 indicated how widespread was general support for a watershed program. The committee reached four conclusions.

First, programs for soil and water conservation and downstream river development are closely related, but a serious shortcoming existed in our attack on the problem.

Second, the shortcoming lay in a lack of purposeful activity in small watersheds. A gap existed between programs to conserve soil and water on individual farms and the big developments on major rivers.

Third, the work in small watersheds can proceed without waiting on major river structures.

Fourth, the planning and installation of upstream programs and projects should be a cooperative matter among the Federal Government, the States, local governments, and the residents themselves. Each, as far as possible, should bear an equitable proportion—based on anticipated benefits—of the cost.

A bill embodying those conclusions was introduced in the 82d Congress.

The Missouri Basin Survey Commission (which included three Senators and three Congressmen) held 17 public hearings in the basin in 1952. A number of witnesses criticized the program that the Congress had authorized for the Missouri Basin on the grounds that an adequate watershed program was not included. The Commission recommended congressional authorization of watershed-management projects in different parts of the basin to demonstrate the usefulness of the proposed land-treatment and water-conservation methods for improving productivity and reducing damage from floods.

More than a thousand organizations actively supported efforts to obtain a national watershed program. Their representatives appeared before congressional committees, the Secretary of Agriculture, and the President to express their views.

In a message to the Congress on July 31, 1953, President Eisenhower urged a program of conservation and development of resources, including a watershed program. He emphasized a policy of Federal, State, and local cooperation.

In the 1953 agricultural appropriation bill the Congress included an item for starting pilot projects on watersheds. Work was started in 62 watersheds.

The Congress passed in 1954 the Watershed Protection and Flood Prevention Act—Public Law 566—with some modifications from earlier drafts. Most important was the emphasis on State and local responsibility. Federal assistance was limited to aiding local organizations in undertaking the work. The 1936 Flood Control Act had carried a requirement that local interests furnish rights-of-way and operation and maintenance, but in it the initiative was with the Federal Government. Now, in the new law, we moved from Federal initiative and responsibility in the selection, planning, construction, and maintenance of the projects to a situation in which the major initiative and responsibility rest with the people themselves and their own organizations.

This policy was reiterated and emphasized by the President in the rules and regulations prescribed December 18, 1954, for administration of the Act and the Secretary of Agriculture in his policy statement of March 14, 1955.

The Watershed Protection and Flood Prevention Act deals with water-management measures that are beyond the abilities of individual farmers but are needed to relate farmers' measures to conserve soil and water with those that involve the watershed community. It bridges the gap between individual farm programs and the enterprises in vast valleys.

It provides for works of improvement that will have greatest significance in small watersheds where soil conservation measures have been applied on most of the farms. It can aid such communities in completing those structures and measures for flood prevention, irrigation, and drainage which must be built by the community. Assistance can be provided only if the benefits of the project exceed the costs.

Local organizations must apply for the projects, must participate in planning, financing, and constructing them, and must arrange for maintaining any works of improvement installed under the act. The works are to be local projects with Federal participation—rather than Federal projects with local participation.

THE LOCAL sponsoring organizations must submit an application; participate in the development of a work plan acceptable to the local organization and to the Department of Agriculture; acquire land, easements, or rights-of-way; assume an equitable share of the project costs; carry out works of improvements and enter into contracts to install structures; arrange for operation and maintenance; arrange for any necessary water rights; obtain agreements to carry out soil-conservation programs from owners of not less than half the lands in drainage areas above retarding dams; and pay any extra cost incurred by inclusion of additional capacity in structures for irrigation or any other purpose not specifically related to flood prevention.

A State agency has opportunity to provide leadership in watershed development. Several States have established soil conservation committees, water boards, natural resources boards, departments of conservation, or other agencies that may fulfill the purpose. Such agencies could coordinate water programs, recommend priorities for assistance, and assist in technical and financial problems. They could help in the formation of local organizations and in recommending ways of operating and maintaining the programs.

Applications of sponsoring organizations for assistance must be submitted for review to the authorized State agency, or to the Governor if there is no such State agency, before assistance may be furnished by the Department of Agriculture.

The States may wish to examine enabling legislation under which local interests may carry out their responsibilities under the act.

The local responsibilities in many instances may be met through voluntary cooperative effort, which is essential to success, but some activities are such that they can be carried out only by agencies created under State law. The local organization must have authority under State law to carry out, maintain, and operate works of improvement. As a first step in qualifying for assistance, farmers in a watershed must create such an organization when a qualified organization or organizations do not exist. Its officers must prepare and submit an application if they desire Federal assistance. There will be no program unless they are interested enough to make the effort to complete the application and give assurance that they intend to carry out their part in making surveys and participating in every phase of the planning.

They must acquire necessary land, easements, or rights-of-way. Owners of the property on which the measures are to be installed may donate the rights-of-way; otherwise, money will have to be raised through taxation or in other ways to carry out the requirements.

The local organization will need to provide cash or other assets for the installation of the improvements before

contracts can be let. When the necessary land, easements, or rights-of-way are considered along with the construction costs, the cash needs may be heaviest in the early years of the program. The power to incur debt and to levy taxes and assessments therefore may be essential if the organization is to perform this part of its responsibility.

The local organizations will have most of the responsibility for entering into contracts for construction of works of improvement, but they will have technical assistance in connection with the expenditures of Federal funds. They will need to make definite provision for day-to-day decisions regarding the construction and make arrangements satisfactory to the Secretary of Agriculture for operating and maintaining the works. Because that annual cost must be met through the years, some legally responsible body must agree to assume the responsibility.

Local organizations must acquire (or provide assurance that landowners have acquired) all water rights that may be needed and must obtain any permits required by State laws for construction of structures.

In order to receive assistance, the organizations have to obtain agreements to carry out recommended soil conservation programs on at least 50 percent of the land in the area affected by the program. That means that practically every watershed program will be installed in cooperation with a soil conservation district. Even if some other type of district is the initial sponsor, it will be found desirable to arrange with the soil conservation districts for co-sponsorship to assure that the required soil conservation program is provided for.

THE RESPONSIBILITIES for functions outlined for local organizations might be performed by local districts with different names or by counties, municipalities, or other forms of local government. To simplify the discussion, we use the term local district to include the bundle of powers needed.

The local district must be created by a State legislature in one of two ways. The first is a special act for each such district, defining its boundaries and powers. The second is a general enabling act, under which local people may establish districts on their own initiative by following specified procedures.

THE SECOND METHOD is more flexible and permits local groups to organize new districts or change the boundaries or powers of existing districts without obtaining special legislation.

If the local district is to be given general powers of taxation and regulation, which could affect almost everyone in the district, the procedures should require that local people approve the decision to organize and other major decisions on taxation and regulation.

The act provides that applications may be for watersheds not exceeding 250,000 acres, but several may be grouped together for planning. The provision does not limit the size of local organizations. One organization could sponsor several watersheds.

The financial requirements make it desirable to have an adequate financial base for the local district. A good many overhead costs will exist regardless of size. In the larger organizations they will be less of a burden. But the community interest may be lost if the organization becomes too large.

In any event, the local people and the judicial or administrative body to which the organization petition is addressed should have authority to determine the size and boundaries of each district. Natural watershed boundaries must be followed in planning a program; they cut across boundaries of counties and townships and other units of Government.

The objectives of the local district might be stated as flood prevention, water management, drainage, and irrigation through the conservation of land and the installation of structures.

The local district will need some

broad powers, including the rights to enter into contracts and agreements; to sue and be sued in its corporate name; to acquire, hold, and sell real estate and personal property; to exercise the power of eminent domain; to accept gifts and grants from State, Federal, and private agencies; to hire and discharge employees and fix their compensation; and to establish regulations for the conduct of the district's business, which are not inconsistent with the purposes of the district and the provisions of the enabling act.

An important function of the local district will be to work with all agencies, public and private, whose activities within its boundaries have a bearing on watershed protection, flood prevention, soil conservation, drainage, and irrigation. Much of the district's work therefore will be negotiation of agreements with Federal departments, State agencies, municipalities, and local organizations, such as conservation districts, highway departments, boards of county commissioners, drainage and levee districts, and irrigation districts.

THE DISTRICT'S REGULATORY authority may not extend beyond its boundaries, but it should be given the right to enter into agreements with governmental units outside its boundaries, including those in other States. District boundaries may not cross State lines, and when the natural boundaries of a project area or watershed lie in more than one State, it may be desirable to organize local districts in each State and arrange interdistrict cooperation.

The district should have the power to conduct surveys and to design and construct works of improvement. Under the act, the Federal Government will furnish the local organization technical and financial assistance in construction, but the local district should be in position to cooperate in or to undertake any work not handled by other agencies.

As we indicated, the operation and maintenance of structures will be an important function of the local district. Not only must it have the power to operate and maintain works constructed by the district; it must also operate, maintain, repair, rebuild, and replace structures constructed with assistance from the Federal Government and other agencies.

Powers of taxation and special assessment will be important. Very likely the local district will have to finance a large part of the local contribution to the program, either through general taxes levied on property in the district or through special assessments levied against benefited lands. The legal limitations on the district's taxing powers will establish limits on the amount of work the district can do.

The history of water conservancy districts has demonstrated the advantages of a combination of both general taxes and special assessments in a resource development program. One arrangement would be to permit general tax rates high enough to cover overhead and administrative expenses and some of the survey and planning costs and to supply a reserve for maintenance.

It may be desirable also to permit (or even to require) the district to levy an additional general property tax for debt reduction in the event that it defaults on its indebtedness. That would make its warrants and bonds more attractive.

Probably a major share of the contribution of individual landowners to the costs of installation and maintenance of the larger structures will come through special-benefit assessments. Equitable assessment depends on an accurate evaluation of the benefits to occur to each tract of land. Satisfactory procedures must be worked out for evaluation and assessment of benefits of the watershed drainage or irrigation program.

The district board of directors should be responsible for the determination of benefits. An appraisal board could be established to make the assessments as well as the appraisals for the acquisition of sites, rights-of-way, and easements for works of improvement.

After original determination of the benefit assessments, the district board should hold a public hearing, at which each affected landowner may appear to present his protests. The requirements for notice of the hearing and the way in which the board of directors should certify the finally approved assessment and tax rolls to the county officials for collection should be specified in State legislation.

FOUR TYPES OF DEBT obligations may be provided: Warrants issued to pay bills and registered in anticipation of tax collections in the current fiscal year; general obligation bonds, to be retired from the proceeds of general property tax levies over a period of years; special assessment warrants and bonds, or both; and repayment contracts with a Federal or State agency.

The local district can do much to control the use of land and water resources through its power to contract. In its agreements with individual landowners, for example, the district could require that certain practices be followed or that certain land uses be modified as a condition to the landowner's receiving benefits under the program. The act requires that local organizations must obtain agreements to carry out recommended soil conservation measures and proper farm plans from owners of not less than 50 percent of the lands situated in the drainage area above each retention reservoir to be installed with Federal assistance. Soil conservation districts throughout the country have had considerable experience with district-farmer agreements; in fact, such agreements are the central core of their program. Few districts, however, have attempted to enforce those agreements by legal action.

Another way in which the public's investment in works of improvement may be protected from improper land use on the watershed above structures is through the use of regulatory powers.

The State may regulate the use of property in the interest of public health, morals, safety, or the general welfare. Those regulatory powers may be delegated by the State legislature to local governments by a general act, which would permit the local unit to exercise specified controls, or enabling acts, to permit the local units to adopt zoning ordinances and land-use regulations.

It might be desirable for local districts to have certain specified regulatory powers (the control of water levels in reservoirs, for example) and in addition grant districts the optional power to enact rural zoning and land-use ordinances.

MANY STATES are studying the problem of providing for the creation of local districts. Major questions are whether existing laws are adequate, whether it would be better to amend some existing law or whether new laws are necessary. A study of the actions of those State legislatures that met in 1955 indicated no clear-cut acceptance of any single way to solve the problem. A few States have enacted legislation pertaining to watersheds and flood control districts. Others amended existing legislation for drainage, water conservancy, and flood control districts. A number of States amended existing legislation regarding soil conservation districts. With regard to the latter, action was taken in two States to provide for the creation of watershed sub-districts of soil conservation districts. Several States took no action. In some States, it was considered desirable to initiate the program under existing legislation pending studies of needed changes.

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Floods—and a Program To Alleviate Them

Erwin C. Ford, Woody L. Cowan, and H. N. Holtan

Damage from floods has been rising for a number of years. The reason is not necessarily that the flood volumes have changed but that the floodplains have increased in value.

Floods occurred before man's occupancy of this Nation began, but then the bottom lands of rivers and streams were not occupied by farms and cities, and damage was not measured in lives and money. The problem of floods has grown as we have contested Nature's delegation of certain lands to floodways, and have settled along streams, put utilities on the streambanks, and established farms over adjacent areas.

As operations, installations, and investments developed and grew, the floodplains became more and more important to our national economy. A high proportion of the industries located thereon are now considered vital to our defense. More than 5 percent of our agricultural lands are on floodplains of small streams. A large flood in most valleys and tributary streams today, therefore, may be a disaster.

The size of a flood depends on the rate, duration, and extent of rainfall and the condition of the land on which it falls. Point rainfall is greater than average rainfall over a sizable area; that is, there are storm centers in which rainfall is greater than it is in the surrounding areas. The path or direction of movement of the storm center greatly influences the magnitude of any resulting flood. Storms of high intensity usually are short and localized and occur in summer. The so-called general rains cover more territory but are of less intensity and last longer than the "cloudburst" type of storm.

Flows from small drainage areas respond more quickly to rainfall intensities than do the flows from large areas because of the shorter distances of flow. That and the higher rainfall intensities on small areas cause relatively higher peak flows per unit area from small watersheds. It also leads us to expect floods from small areas during summer cloudburst storms and floods from large areas during long, cool-season rains. Occasionally a cloudburst storm will travel a path that follows the direction of drainage for a large area, and a series of small-area floods thereby contributes to flow in the main stream.

If the storm travels at a speed which causes flood flows from several small tributaries to reach the main stream at about the same time, a major flood may occur. Most of the summer storms are localized, or their paths do not coincide with a large drainageway to produce major floods. So, in general, the major floods covering large areas usually occur during long storms.

THE TERM FLOOD is not synonymous with some specific rate of flow. What may be a flood at one section of the stream may be well-controlled flow at another section. Flooding will result from a reduction in channel capacity because of any one of a number of physical conditions, such as a reduction in gradient, barriers to flow, meander or changes in direction, an undefined channel, or the siltation of a channel.

Flooding might be induced at one section through the upstream channel characteristics that tend to speed up flow. The removal of some barrier by force of the flow or improvement of the hydraulics of a reach through scouring, for example, may speed up flows to the extent that subsequent sections downstream cannot carry them. Thus the flooded section may shift over a period of years from one place to another along a stream bed that is not stable.

Confluences of tributaries are potential flood areas. As already mentioned, the flows from tributaries may be induced by storm travel to coincide and result in a flood from a local storm. On

a larger scale, the flood works at the confluence of the Missouri River with the Mississippi north of St. Louis, Mo., and of the Ohio River with the Mississippi at Cairo, Ill., are efforts to control the floods that occur when tributary peaks coincide with peak flows on the main stem.

HARDLY A YEAR goes by in which we do not have one or more disastrous floods somewhere in the United States. Such a flood may affect only a small area, or it may strike a great river basin like the Columbia, Missouri, Mississippi, or Ohio. A great flood in the Missouri River Basin in the spring of 1952 caused damage to agricultural land alone of about 100 million dollars.

The Columbia River Basin had the most damaging flood in terms of monetary losses in its history in the spring of 1948. It inundated Vanport, Oreg., parts of Portland, and other cities, towns, industrial developments, and farms, took more than 40 lives, made 60,000 persons homeless, and caused property damage estimated at 200 million dollars.

The flood was the result of abnormally heavy precipitation during the preceding 9 months, abnormally heavy snowfall in the mountains during the winter and spring, an abnormally cool spring season, the sudden arrival of hot weather in the entire watershed beginning May 17, and many thunderstorms, with very heavy rains all during May in all parts of the Columbia River Watershed.

The unusually heavy precipitation and the excessive snow pack, without which such a high peak flow would not even have been possible, were accentuated in the northern part of the Columbia River watershed. The part of the watershed in Canada had equally abnormal precipitation and an excessive snow pack just before the flood. There was little or no excess in the southern one-fourth of the area. Normally the peak snowmelt flow of the southern part of the watershed precedes the peak for the northern tributaries, but that year several peaks reached the lower river almost simultaneously. Because of widespread floods in the upper tributaries, the time of the floodwaters in the lower reaches could be forecast readily and rather accurately. Nevertheless, heavy damage occurred, because man had moved in on the river bottoms with intensive industrial, residential, and agricultural use in the fallacious belief that the lands under dikes were safe.

Even greater damage to the land resulted. Indications are that the damage to the land exceeded all damages to man and his cultural developments.

A flood of the Kansas River in 1951 caused losses in the creek bottoms and small stream valleys, above the points where major control works have been recommended, estimated at 102 million dollars. Total losses from the flood were estimated from 800 million to 1 billion dollars. About 35,000 houses were flooded, and at the peak of the flood some 250,000 persons were driven from their homes.

The rains responsible for the flooding of the Kansas River began falling in late April. They continued off and on through June, and culminated in heavy downpours between July 9 and 13, 1951. Rainfall in May averaged 6.43 inches—2.66 inches above normal.

Many of the streams in the area reached flood stage in May, and flash floods on small tributaries caused severe damage. June was the wettest month in 65 years of weather history in Kansas; an average of 9.55 inches, 5.58 inches above normal, fell.

THESE WERE, indeed, great floods, and each was a disaster of the first magnitude. Less spectacular are the many floods that occur year after year within the tributary headwaters of our major rivers, but they cause a larger total damage.

Preliminary estimates indicate that the total average annual damage from floods and sediment in the United States approximates slightly more than 1 billion dollars.

The total varies from year to year. Flood damages, including the flood in the Columbia River Basin, were estimated to be below normal in the first part of 1948, but in 1947 damages in the upper Mississippi, Missouri, and southern Florida areas alone greatly exceeded the longtime average for the entire country.

Estimates prepared by the Soil Conservation Service in 1952 indicated that the annual loss to agriculture alone is about 557 million dollars. The estimates were developed from studies covering 15 years and 77 watersheds, whose area is about 52 percent of the continental United States.

Agricultural losses from floods are of several kinds—damage to crops and pastures; land damage in the form of floodplain scour, streambank erosion, gullying, and valley trenching; infertile overwash or deposition of sediment and swamping; damage to farm buildings, fences, roads, stored crops, livestock, irrigation, and drainage facilities; and indirect losses, such as delays in field work and disruption or delays in marketing of farm products.

The toll can be divided into two parts—the upstream damage in tributary or headwaters of major rivers and damage that occurs downstream, or in major river valleys. In general, the term upstream refers to areas above existing or proposed major flood control structures, and downstream to areas below such structures.

The average annual upstream damage is estimated to be about 545 million dollars. There also are sediment damages of 100 million to 130 million dollars annually.

Upstream flood losses are greatest in the Mississippi-Missouri Valley States. Losses also are heavy in the Gulf Coast, South Atlantic, Arkansas River, Red River, and Eastern Gulf areas.

In the Pacific Coast States and North Atlantic Coast States, nonagricultural damages exceed agricultural damages. In most other areas of the Nation, agricultural damages exceed nonagricultural damages by a substantial margin.

Floods on creeks and small tributary streams occur oftener than do storms of longer duration over large areas, which are necessary to produce a major downstream flood in a large river. A large share of the headwater flood damage results from floods that occur oftener than once in 10 years. Because thousands of headwater streams drain our vast agricultural regions, the damage caused each year by many such floods builds up to a large total.

A major part of the damages in headwater valleys is agricultural—nearly 70 percent of the total annual average damage. Damage to growing crops and to pasture constitutes about 45 percent of the total. Damage to land is important from the viewpoint of our total agricultural resources, because the land in the alluvial floodplains of creeks and rivers usually is highly productive. With a reasonable degree of flood protection, it will remain productive for many years to come. Damage to agricultural property in upstream areas amounts to about 15 percent of the total annual average.

The annual damage in the major river valleys is estimated to be about 500 million dollars, of which about 165 million dollars is agricultural damage. The annual downstream sediment damage approximates 28 million to 30 million dollars. The sediment damages are largely nonagricultural.

A LARGE AMOUNT of protection has already been provided to major river valleys by levees and flood walls, channel improvements, and major reservoirs. Were it not for this protection, downstream damage would be much greater than it is now.

The division of flood damages between upstream and downstream areas indicates two major problems—the problem of reducing flood damages in the upstream headwaters and the problem of providing protection to the great river valleys downstream with their high concentration of wealth and population.

Because a large part of the damage occurs in valleys of headwater streams and affects agriculture and agricultural interests, added emphasis should be given to the protection of watersheds and prevention of floods in those areas.

Protection from destructive floods is a recognized Federal responsibility in the national interest, because floods affect all of us directly or indirectly. A coordinated Federal, State, and local partnership approach is required in order to reduce the heavy toll of damage caused by floods.

Could a different way of using the land have modified or prevented the Kansas flood in 1951? It was caused in large part by great quantities of rain falling on soil already fully charged with water. The small rain-swollen tributaries converged to swell and overflow the main channels so fast that the flood waters could not be diverted. The best kind of land use would have had only minor effects on such a flood.

Several factors determine the part that land treatment has in preventing floods. First are the factors that cause floods; the factors that man cannot control or change—climate, rainfall, geology, topography, the size and shape of the watershed—and those he can control.

The factors man can change are few, but important. They comprise his own use of the land—what he does to the soil and vegetation it produces—or, simply, the treatment of the land, which means the vegetative and simple mechanical measures that conserve soil and water, increase the rate at which soil absorbs water, and improve the storage capacity of the soil. Such measures include contour-tillage, crop rotations, contour furrowing and listing, stripcropping, green manures, cover crops, level terracing, reseeding, proper management of range and pasture, reforestation, forest and woodland protection and management practices, and such minor structural measures as gully plugs, diversions, diversion outlets, and grade stabilizers.

For more complete watershed protection, however, those measures must be supplemented by, or combined with, water-retarding and disposal structures in farm drainageways, along roads, and in the smaller streams.

This second category of measures is planned primarily for the management of waterflow after it has left the fields and farm waterways and reached the small branches and creeks. They include floodwater-retarding structures, stream-channel improvements to increase carrying capacity and stabilize beds and banks, minor floodways, sediment-detention basins, and similar measures. The distinguishing characteristic of this group of measures is that their primary benefits are off-site or downstream, not at the places where they are installed. In a sense the primary benefits are public, because they accrue to other farmers, towns, roads, and so on, downstream from where the measures are installed.

Some of the measures, which are needed for stabilization of watershed lands, are too complex for landowners to install, or the benefits will be so long deferred that it is unreasonable to expect very many farmers to do these jobs without assistance. For example, reinforced concrete structures needed to stabilize large gullies require all the elements of planning, design, and supervision of construction that go into a major flood-control dam. The benefits from this type of gully control are primarily to watershed lands that would be destroyed by the headward growth and enlargement of the gullies. And these lands may be on other farms above the present gully head. If economically justified in the public interest, it becomes more efficient and economical for the installations to be made by agencies of Government under binding maintenance agreements.

The measures that are primarily for flood prevention, such as retarding structures and channel improvement, can rarely be installed by individual landowners. They require group action, skilled technical planning, and corporate or governmental financing.

For 20 years the Federal Government has been carrying out programs of aid to individual landowners and operators in establishing or applying conservation measures that meet primary objectives of flood prevention; namely, increasing the infiltration of rainfall and the water-holding capacity of the soil. The programs have been carried out under national authorizations, such as the Soil Conservation Act of 1935. Under this authority, the Soil Conservation Service, for example, in 1955 provided technical assistance to nearly 2,600 soil conservation districts, which include 84 percent of the agricultural land of the Nation. As of June 30, 1954, 1,454,000 farmers and ranchers, operating 423,690,000 acres of land, cooperated with the districts.

In addition, the Production and Marketing Administration, through its agricultural conservation program, has been giving assistance in more than 3,000 agricultural counties by making payments for part of the cost of application of conservation practices.

A large part, if not the major share, of work done under these programs has helped prevent floods.

But very little has been accomplished so far by the Federal Government in aiding in the installation of measures for watershed stabilization and flood prevention that are beyond the capacity of individual landowners and operators to install, either because they are too complex or too costly to the individual or because they produce benefits that are either mainly off-site or are long deferred.

Since about 56 percent of the current average annual floodwater and sediment damage occurs in the valleys of headwater streams and since a large part of this damage is agricultural and primarily affects agricultural interests, it appears that additional emphasis should be given to the prevention of upstream floodwater and sediment damage.

Federal appropriations have provided about 63 dollars for flood control on main streams to every dollar for upstream watershed flood prevention. There is need for an interrelated threefold program, each part of which would be given proper weight in terms of public assistance and would be coordinated with the others to the fullest degree possible. These are:

Land treatment. Land treatment includes contour cultivation, terracing, improved rotations, cover crops, improved range management, woodland management, and many others. Such measures, in proper combination, help prevent erosion, maintain soil fertility, conserve water by storing it in the soil, prevent damage on the farm from the erosive action of rainfall and runoff, and reduce the sediment loads of creeks and rivers. Land treatment measures are being rapidly installed by landowners under the programs of the soil conservation districts, aided by technical assistance from the Department of Agriculture as well as by educational assistance and direct financial aids from others. The rate of application needs to be stepped up, however, to achieve more rapid protection of watershed areas.

Upstream waterflow retardation and channel stabilization. This phase of watershed improvement, involving work on the tributaries and smaller waterways to control or retard runoff from neighboring farms, includes small retarding structures, gully-stabilization works, and channel improvements, which are installed largely by contact, to alleviate damage to the agriculture and to rural improvements of the smaller watersheds above the downstream engineering works. These measures retard runoff and stabilize sources of sediment in upstream channels. They represent water-control operations over and above what is ordinarily done through the farmland conservation job. This type of work is now being carried out in a few watersheds by the Department of Agriculture, assisting local agencies and individuals.

Downstream flood-control measures. Large reservoirs and levees constructed on the major waterways control flood

flows in the major river valleys. Such measures alleviate urban and agricultural damages caused by major floods lower down the main rivers.

This three-phase program is a coordinated approach to flood prevention and control—a program that protects the farmer or rancher of the uplands as well as of the lowlands, and the upstream bottomlands as well as the downstream cities.

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The Possibilities of Land Treatment in Flood Prevention

Howard O. Matson, William L. Heard, George E. Lamp, and David M. Ilch

In most tributary valleys, 75 to 90 percent or more of the total flood losses are caused by the comparatively small storms that occur on an average of once in 10 years or oftener.

If overflow in tributary valleys could be reduced to not more than once in 10 years, the risk of flood damage would be no greater, in general, than such other agricultural risks as drought, hail, early frost, lightning, and pests—risks that the farmer takes year in and year out. Often land treatment alone, but generally augmented by small waterflow-retarding structures and stream channel improvements, can provide enough flood protection in the headwater areas to reduce the risk to what the farmer faces against other natural forces.

A flood produced by a thunderstorm usually results when a center of intense rainfall develops at or near the center of a small watershed. Intense rainfall centers ordinarily move at about 15 to 25 miles an hour, and if the storm path follows down a watershed, the severity of flooding is greatly increased. Maximum rainfall during a thunderstorm is rarely more than 12 to 15 inches, although depths exceeding 30 inches in less than 24 hours have been reported.

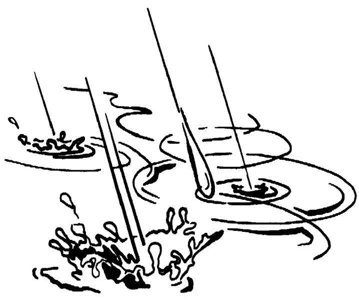
Floods of great magnitude on major rivers are produced only by general storms that persist for several days. When such storms occur in late spring, the flood volume may be increased by melting snow.

The frequency and severity of flooding are greatest in regions next to the Gulf of Mexico, where intensities of rainfall generally are higher than in other regions. Rainfall intensities decrease gradually northward from the Gulf and are higher over the eastern and central parts of the United States than in the territory between the Great Plains and the Sierra Nevada.

Other factors may be important, but the frequency of flooding generally is directly related to the frequency and characteristics of storms. Another factor is the relationship of the channel capacity of a stream to the size of its watershed area. In the Sandstone Creek watershed in western Oklahoma—typical of many small streams in that area—a runoff volume equivalent to one-fourth inch of rainfall from the watershed area was enough to cause flooding under average conditions. As a result, flooding occurred an average of more than nine times a year.

Rainfall occurring before a potential flood-producing storm affects the soil moisture and thereby the rate and volume of runoff that may result from the flood-producing storm that follows. Any effective antecedent rainfall—generally more than one-half inch in 24 hours within 10 days before a flood-producing storm—is usually significant in limiting the soil storage at the time of the storm. The amount of antecedent rainfall that might be

Let the Land and the People Rejoice



This is an account of a program to improve a pilot watershed in Ohio. It is an example, a guide, a lesson. The facts it brings out can be applied to watersheds all over our country.

The Upper Hocking watershed lies west and north of Lancaster, Ohio, the seat of Fairfield County. Its area of 31,418 acres (49 square miles) includes 27,700 acres of farmland, a part of Lancaster, and 3,202 acres of flood plain. The bottom land is intensively cultivated; about two-thirds is in grain each year. Some 44 wholesale, retail, and small manufacturing concerns are on the flood plain within the city.

In the past, any storm that produced 6 inches of runoff inundated the flood plain. Floods have been frequent along the Upper Hocking and Hunters Run, which joins the main channel in Lancaster. Damage caused by a flood in 1948 was set at 1 million dollars. Damages from floodwaters and sediment have averaged 100 thousand dollars a year—somewhat more than half to property in Lancaster and the rest to crops, pastures, farm improvements, and transportation. Gullies are common on the watershed. The slopes have lost up to half the topsoil through sheet erosion.

A watershed-protection program was developed jointly by the local people, the Fairfield Soil Conservation District, and the Soil Conservation Service. Its purpose is to prevent floods and to hold soil and water on the watershed.

The program includes nine drop-inlet dams, which are earth dams with small outlet conduits. They hold back floodwater from a 6-inch runoff long enough so that the water can flow through the conduits slowly, without damage. Structures to control sediment are being built. Stream channels are being improved. Critical sediment-producing areas are being stabilized.

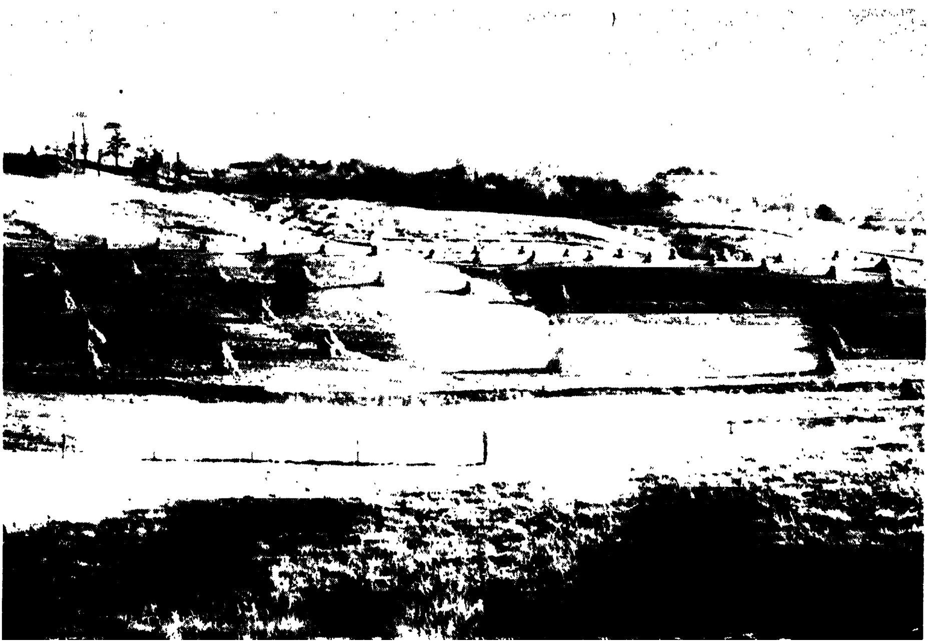
Conservation measures include adjustments in land use, stripcropping, terrace outlets, terraces, farm waterways, seeding of pastures, field diversions, and planting of trees. A fire-control program is being developed. Help in managing forests and woodlots is given landowners.

Residents expect the completed program to yield benefits worth 98 thousand dollars a year in watershed protection, a net increase in farm income of 84 thousand dollars, and a reduction of 87 percent in annual damage from floodwater.

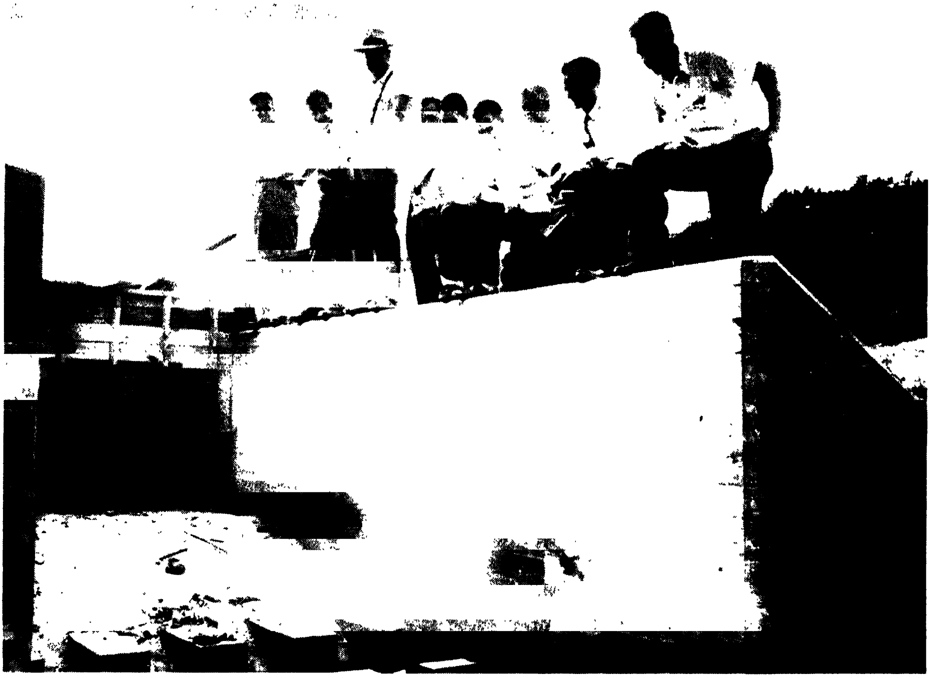
The total cost of the flood-prevention and conservation measures has been estimated at 1.5 million dollars, shared nearly equally by the residents and the Federal Government.

The bottom lands and rolling uplands of the Upper Hocking watershed support general grain-livestock farming on 287 farms, whose average size is 150 acres. From Mt. Pleasant Park one can see a part of Lancaster, a city of 26,500 population. Hocking River and Hunters Run join in the lower part of Lancaster. Their floods have kept in jeopardy the homes and businesses on the flood plain there.

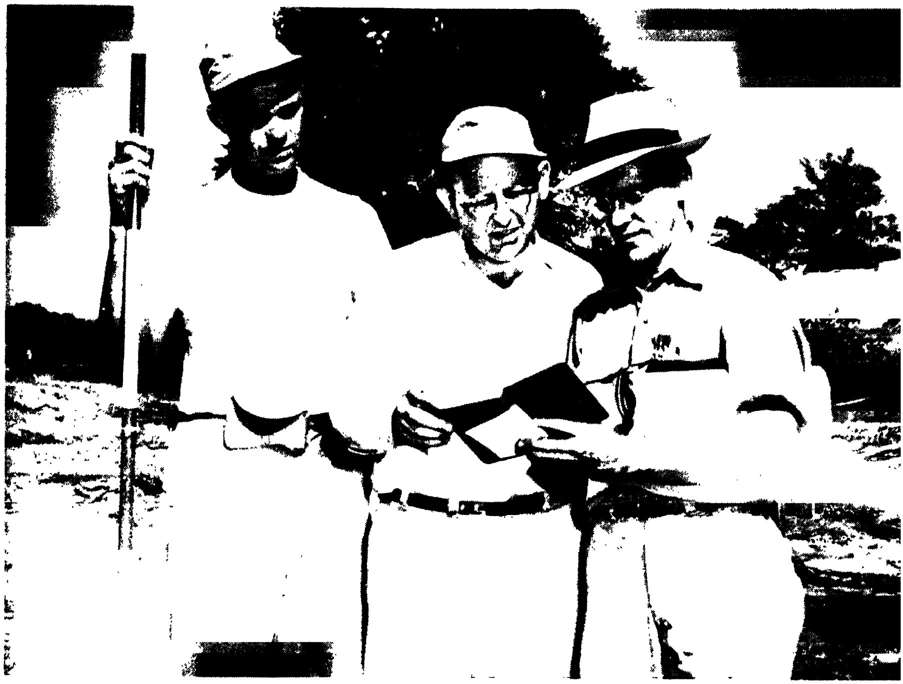
Large gullies may occur on unprotected land. Every heavy rain cuts them deeper. Soil carried from such gullies by floods to lowlands damage the flood plain and must be removed at great cost. Summer storms harm clean-cultivated crops, such as corn. Sheet erosion and incipient gullies may not appear serious at first, but before long they lower crop yields and productivity of soils.



Lancaster suffered a serious flood on July 22, 1948. Small houses were washed from their foundations. Railroad property was damaged. The products of lumbering and other businesses floated away or were buried in the debris and sediment washed down from the uplands.



As the watershed-protection program of the Upper Hocking got underway, farmers and businessmen took an active interest in the work. Here a group is inspecting the concrete dissipator blocks used in the outlet of the first dam to be constructed. Crop inlets, of concrete, provide for a slow, uniform passage of runoff waters into the channel below. The concrete work is finished before the embankment or earth fill is constructed to form the dam.



Engineers of the Soil Conservation Service checked the contractors' work on the dams, nine of which were planned for the watershed, at a cost of about 900 thousand dollars. The surfaces of the completed dams are protected by seeding with grass to prevent erosion. Baled hay is spread as a mulch to help the grass get started.

Work to conserve soil and water on the farms in the watershed has been carried out simultaneously with flood-prevention measures. One practice was to make open drains to eliminate soggy meadows and increase production. Outlets provide safe methods of water disposal for the field waterways. Waterways were graded into former gullies and natural water courses. Grassed waterways are left as a permanent protection to the land and are not plowed during cultivation of fields.

Contour stripcropping protects fields where clean-cultivated and close-growing crops are raised in rotation. The force of water running across bare soil is broken when the water reaches the alternate grass strip. The grass holds some of the water and filters out dirt. Farmers in the Upper Hocking watershed plan to stripcrop about 5,000 acres. Trees planted on otherwise idle land also will help reduce erosion and runoff. Farm ponds are used for stock water, recreation, and other purposes. Ponds can produce up to 200 pounds of largemouthed bass and bluegills per surface acre of water.

considered effective, however, varies from place to place and from season to season. The occurrence of effective antecedent rainfall can be a significant factor in limiting the effectiveness of land treatment.

Generally, land treatment is most effective in reducing the runoff from long-continued rains of moderate intensity and have the least effect on the rates and volumes of runoff resulting from short, intense storms. For example, Ralph W. Baird, project supervisor at the Blacklands Experimental Watershed, near Waco, Tex., reported that conservation practices have reduced peak rates of runoff appreciably and that the reduction in peak rate is a relatively constant amount—about 0.5 inch an hour. This means that a peak rate of runoff of 1 inch an hour would be reduced to 0.5 inch, but a peak runoff rate of 3 inches an hour would be reduced only to 2.5 inches an hour.

THE SIZE AND SHAPE of watersheds are permanent characteristics that influence mainly the concentration or time distribution of runoff from a watershed. The size and shape of the watersheds greatly affect collection and discharge of streamflow. Surface runoff in some watersheds is quickly assembled and discharged. In some others, the surface drainage is longer delayed and the discharge released more slowly. Part of this influence is due to the soil characteristics. As watersheds increase in size, they become more complex with regard to slope, topography, soil, and the vegetative cover conditions. Many streamflow characteristics are related either directly or indirectly to topographic features which cannot be modified greatly by land treatment.

Steep slopes generally have limited surface soil storage; therefore discharge is usually rapid. This is particularly true of short, steep slopes. The runoff from a long slope is usually slower but lasts longer after the rainfall ceases. The effect of slope will vary with the rate and duration of the rainfall. During periods of prolonged, intense rainfall, when runoff usually becomes a constant, the effect of slope is less pronounced; the converse is usually the case during storms of short duration. Steepness of slope is frequently a limiting factor in the application of land treatment measures which would be most effective in reducing runoff.

Return of all the land to its original pristine condition in order to attain the optimum natural control of water is neither practical nor desirable. The land must be considered as it is today—as it is now used—and in this setting we must try to maintain or improve its productive capacity as well as to improve its hydrologic functions in flood prevention. Because it must continue to be used, and because it is made up of a complex number of elements, there will be distinct limitations in accomplishing the maximum that the land is capable of in reducing runoff and erosion.

Various means have been devised to protect the cultivated soil while continuing to grow crops. Steep, cultivated lands have been terraced instead of simply growing crops on the natural slopes. Contour cultivation is now accepted as distinctly better than cultivation up and down the slope. Stubble mulching, working crop residues into the soil, and various other ways of adding plant material to the soil surface are now recognized practices which stabilize the soil and keep it absorptive of water. Periodically changing from clean-cultivated crops to close growing plant covers is effective in reducing the eroding effect of heavy rains. Breaking the length of clean-tilled slopes with strips of sod is also useful in reducing the soil losses. Listing, strip cropping, green manures, cover crops, and similar practices are used to prepare the soil to absorb water better at the same time it is being used to produce food crops.

Conclusions drawn from rotation studies conducted in various parts of the country indicate that surface runoff and erosion are generally reduced, often as much as 50 percent, by rotations that include one or more years in

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close-growing vegetation when compared with land continuously row cropped and that the greater reductions occur when the rotation is in hay or pasture crops. In some cases row crops grown in rotation released as much surface runoff and erosion as when they were grown continuously.

Strip cropping appears to have less effect in reducing surface runoff than rotation cropping, but generally it reduces erosion markedly. Strips of close-growing vegetation filter the soil from runoff water entering them from above and protect the soil in the strips from erosion. Strip cropping seems to be a better practice than rotation cropping for erosion control. For adequate surface runoff control, strip cropping should be supplemented with other control measures.

Contour cultivation has reduced the runoff from rains of low and medium intensity as much as 80 percent when compared to the surface runoff from similar fields plowed up and down the slope.

Changes in the composition and the density of the forage cover are due only in part to the consumption of the forage by the livestock. Equally important is the effect of soil trampling by animals. Trampling has a direct effect upon the infiltration capacity of soil, because the animals' hoofs compact the soil, making it less receptive to water. Heavy use is generally more conducive to severe soil disturbance than is light use. In either instance, the effects of use are modified markedly by the texture and moisture content of the soil. Dry, sandy soils are little affected by trampling since they can be compacted only slightly. As soil texture becomes finer and the soil moisture increases, the compacting effect of animal hoofs becomes more pronounced.

Treatment of the range and pasture to reduce surface runoff and erosion and to maintain forage plant cover for livestock use can be accomplished in several ways. In some areas the quality and density of forage can be improved by reducing the number of grazing animals or by excluding all animals for varying periods of time. Forage conditions often are improved by seeding, which provides additional protective cover for the soil. Cultivation and soil fertilization in the East have been effective in rehabilitating depleted range and pasture, with attendant reduction in runoff and erosion.

Heavy grazing on many western rangelands has increased surface runoff and erosion, often causing more frequent flash floods, increased damage to lowlands, and rapid sedimentation of reservoirs. The effects have been shown clearly by comparisons among similar lands grazed heavily and lightly or not at all. Total exclusion of livestock for definite periods is effective in improving both forage and hydrologic conditions in certain western areas.

Pasturing of woodlots in the East is not compatible with good control over surface runoff and erosion, especially on hilly land. Trampling compacts the soil, reducing the rate at which water can enter; browsing destroys the soil-protective cover provided by small and young growth, increasing the susceptibility of the soil to erosion. The sod grasses and legumes that make up most of the forage in the humid sections protect the soil well against erosion, if grazing is not too heavy.

Studies on the Coweeta Experimental Forest in North Carolina show the following effects of logging disturbances in steep mountain watersheds: ". . . Over a 4-year period, 2.3 miles of road lost 6,850 cubic yards of soil. During storms, the stream turbidity on the logged area reached a maximum of 7,000 parts per million as compared with 80 p. p. m. for the check (unlogged) area. . . . Flash runoff from the roads has also doubled flood peaks. Although the logged area is still forest-covered and will produce another crop of timber, its water quality and sediment production are more typical of hillside cornfields than of forest."

Land treatment in forest and woodland areas can be aimed at minimizing the harmful effects resulting from the

operations of harvesting the wood crop. Practical methods are now known by which forest lands can be used for timber production and yet contribute substantially to waterflow retardation and erosion prevention. It is possible to improve the hydrologic functions of many of the existing tracts of forest and woodland and to reestablish a protective forest growth on many acres of deteriorated cultivated crop and pasture land no longer usable for that purpose.

To ACCOMPLISH EFFECTIVE land treatment for flood prevention is not simply a question of money—limitless funds would not produce the results without the complete and willing cooperation of the landowner and the operator. The cooperation can be achieved once the land user realizes that erosion and water control on the land will also mean better crops, easier management for him, and a reduction in floods and sediment downstream.

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Frozen Soil and Spring and Winter Floods

Herbert C. Storey

Along with heavy rains and rapidly melting snow as the causes of floods in winter and in early spring, one should consider frozen soil.

Consider first, though, some mistaken beliefs about the occurrence, characteristics, and the effects of frozen soil. Many persons think that if subfreezing temperatures persist for some time, the soil will freeze uniformly over large areas or that once soil is frozen it becomes impermeable and stays frozen until the spring thaw. Some element of truth resides in those ideas: It is true that if temperatures remain below freezing for a time, some soils start to freeze. It is also true that some frozen soils prevent infiltration. It is also true that some soils have remained frozen throughout the winter.

Soil freezing is an important hydrologic factor in the part of the United States where low winter temperatures prevail and the snow cover is light. Its southern boundary is a line extending from the vicinity of New York City southwesterly across New Jersey and Pennsylvania, and west across southern Ohio, Indiana, and Illinois, through the upper part of Missouri and Kansas, then southwest to the Rocky Mountains in the lower part of Colorado, north along the eastern edge of the Rockies into southern Wyoming, westerly to the northeast part of Utah and the southeast part of Idaho, then east and north again along the east front of the Rockies through Wyoming and Montana. Another zone, separated from the main area by the northern Rockies, includes the eastern one-fourth of Washington and a small part of northeastern Oregon.

Soil freezing does occur south of that line, but it is largely intermittent (freezing at night, thawing during the

day) or only infrequently does it have much hydrologic importance.

Four characteristics of frozen soil bear on its part in floods. Its structure determines how fast rain or melting snow can enter the soil. The depth of penetration of soil frost determines how fast the frost leaves the soil during thaws. The persistence of soil frost determines whether soil will remain frozen through periods of snowmelt. The extent of frozen soil indicates how much of a watershed might be affected.

We use four terms to describe the structure of frozen soil: Concrete, honeycomb, stalactite, and granular.

Concrete frost structure has many thin ice lenses and small crystals and is extremely dense. It usually occurs in soils previously frozen and thawed or in soils settled by a heavy rain. It is most prevalent in bare soils or in soils with a sparse cover of vegetation. It is associated usually with freezing to a great depth.

The honeycomb type has a loose, porous structure. It is easily broken into pieces. It is commonly found when freezing is shallow—usually in early winter—and when soils of high organic content are highly aggregated.

Stalactite frost structure has many small icicles that connect the heaved surface to the soil below. The icicles consist of tiny columns often partly fused into sheets or loosely bound blocks. Stalactite frost often is formed during a refreeze of a partially thawed honeycomb structure.

Granular frost consists of a loose, porous arrangement of small granules or crystals of ice scattered through the soil. It usually occurs in shallow freezing in soils high in organic material. Granular frost often precedes the formation of honeycomb frost. It is quite easily penetrated by a spade or soil auger and may be broken into pieces.

Frost penetration expresses the depth of soil freezing. Deep penetration is associated with dense, impermeable frost and with long persistence, and thus is important as an indicator of structure, persistence, and extent.

Persistence is an important characteristic, because if an impermeable type of frost structure continues through the period of snowmelt, runoff will be high. Even if the frost has melted partway down from the surface, movement of water down through the soil will be prevented or retarded until the frost goes.

The extent of impermeable frost is an important index of how a watershed will respond to a storm or period of snowmelt. A watershed whose soil is nearly 100 percent concretely frozen yields a much higher runoff in a storm than one only 25 percent of whose soil is frozen, even though the penetration of frost in the latter might be greater than in the first.

Frost structure has much to do with the winter infiltration capacity of soils. Concretely frozen soils are relatively impermeable, but the other frost structures seem to have little effect on water movement into and through the soil. As little as 1 inch of concrete frost prevents infiltration of rain or melting snow.

The effect of soil freezing in retarding percolation is greater for heavy-textured soils than for light-textured soils. When concrete frost is present during storm periods, surface runoff—often as much as 100 percent of the precipitation—results. Measurements made during a flood period in March 1936 in southern New York showed that 100 percent of the rainfall ran off concretely frozen bare fields and that little or no runoff occurred on nearby unfrozen, forest-covered soils.

Measurements made in 1941 near Cohocton, N. Y., showed that the runoff from three small cultivated watersheds was directly related to the areal extent of the frost in the soil. In one drainage, where 25 percent of the area contained frost during the melt period, the runoff amounted to 12 percent of the total rainfall and snowmelt water. Where the frost covered 63 percent of the area, the runoff amounted to 41 percent of the available water.

Where frost was found on 93 percent of the area, runoff was 53 percent of the available water. Thus the presence of frost over extensive areas in a small drainage increased the runoff 3 to 4 times.

A COVER OF vegetation and snow greatly influences the structure of frozen soil and the penetration, persistence, and extent. A litter of pine needles can keep the soil from freezing hard—the intergranular spaces of the litter-covered soil are not filled so noticeably with ice as occurs in soil from which the litter is removed.

Concrete freezing has been observed most frequently in cultivated fields. Honeycomb and stalactite frost, which usually occur during shallow freezing, are found most frequently in meadows and pastures. In forested areas frost of the granular type is found oftenest. Honeycomb frost is next in frequency.

The type and composition of the forest cover, the condition of the stand, and the forest floor have a great bearing on the type and degree of soil freezing. Measurements of soil freezing during the winter of 1950–1951 in New York and New England show the general relationships between forest type and concrete soil freezing. Observations of soil frost were made in southern New York on plots covered with hardwoods, of pole and sawtimber size, and on other plots covered with comparable coniferous stands. Concrete soil freezing began to form under the coniferous stands 2 and 3 weeks before any was observed in the hardwood stands. The maximum depths reached in the coniferous stands were about 3 to 4 times greater than in the hardwood stands. All concrete frost had disappeared from the hardwood stands 3 to 4 weeks before it disappeared in the coniferous stands. During the time that concrete frost was present, about 25 percent of the hardwood-covered area contained frozen soil, but 50 to 75 percent of the area in the coniferous-covered area was concretely frozen.

Measurements of soil freezing were made that winter in two plantations of white pine in northern New York. One was 20 to 25 years old. The second was about 35 years old. Concrete frost started forming a few days earlier in the young plantation, was 2 or 3 inches deeper than in the older stand, and disappeared 3 or 4 days later than in the older stand. Both plantations had considerably less frost than nearby open land, but they had more frost than areas that had been continuously in forest.

In various parts of the country, especially in the Northeast, sizable areas of abandoned farmlands are found. Good stands of trees are becoming established on some of the abandoned fields, but little or no reproduction has occurred on other areas. Measurements of soil freezing were made in 1950–1951 in western Massachusetts in areas with and without good natural hardwood reproduction. The regions that had a good stand of natural reproduction started freezing concretely nearly a week later than those with no reproduction; the depth of penetration was 2 to 4 inches less on the area with natural reproduction and disappeared 10 days earlier in the spring.

The effect of disturbance of the forest floor by fire was determined by observations during the same winter on two areas in northern New York. One was covered with an undisturbed coniferous sawtimber stand. The second was covered with a coniferous sawtimber stand from which a large part of the litter and humus had been removed about a year earlier by a fire. Concrete freezing started in the burned area about 2 weeks before it started in the unburned area, was 3 or 4 times deeper, and lasted 2 or 3 weeks longer in the spring.

The effect of disturbing the forest floor by removing or destroying the litter and humus other than by fire and by compacting the soil was determined by the measurements on three stands of hardwood saw timber in northern New York. One stand was

comparatively undisturbed. The second had been selectively logged 2 years earlier. The third had been heavily grazed. The concrete freezing started about 2 weeks sooner in the grazed area than in either of the other two areas, reached a much greater depth, lasted about 3 weeks longer than in the logged area, and about 6 weeks longer than in the undisturbed area. There was more concrete freezing in the logged area than in the undisturbed area, but most of the concrete freezing occurred in the places where skidding of logs had removed the litter and humus and tended to compact the soil—the result there was a patchy pattern of concrete frost.

THE OBSERVATIONS made in the winter of 1950–1951 in the Northeast may be summarized thus:

Less concrete frost forms in hardwood stands than in coniferous stands of a comparable size.

The establishment of the coniferous plantations retards the formation of concrete freezing, as compared with open land conditions, but does not shorten the time when the frost leaves the ground in the spring. Coniferous plantations seem to retard the formation of concrete frost less than does the natural development of hardwood reproduction.

Establishment of hardwood tree reproduction on abandoned fields will reduce the amount of the concrete soil freezing.

A disturbance of the forest floor, by the destruction or removal of litter and humus and compaction of the surface mineral layers, greatly increases the amount of concrete freezing. The amount of concrete freezing is directly proportional to the degree of disturbance of the forest floor.

Concrete freezing of the soil in open lands develops sooner than in forested areas and is deeper and more widespread. Concrete frost disappears in the spring from open lands as soon as in the dense coniferous stands—sometimes sooner.

Well-stocked hardwood sawtimber stands, if ungrazed, have less concrete soil freezing than any other land use or condition.

MANY OBSERVATIONS on the structure of frost were made in New England during the winter of 1945–1946. In open areas the frost was either of a solid or concrete type of structure from the surface down to its full depth of penetration, or of a loose structure in the upper 3 or 4 inches, and solid at the greater depths. The concrete type usually occurred in cultivated fields. The loose type usually occurred in meadows where there was abundant humus. Only occasionally was a concrete type of structure found in a wooded area that had a good deal of organic matter. The most notable exceptions were spruce flats that had high water tables; there the soil was frozen rather solidly to depths of more than 12 inches.

Frost tends to form in a granular or honeycomb structure in soils containing considerable humus. The incorporation of organic matter into a mineral soil by natural processes may cause aggregation of the soil particles and thereby increase the noncapillary pores of the finer textured soils. The reduction of percolation rates is more marked in finer grained than in coarse-textured frozen soils. Since coarse-textured and aggregated soils generally contain larger and more noncapillary pores than fine-textured soils, it is possible that soil structure, as influenced by organic matter, is also a factor in the determination of frost structure.

Available data indicate that:

A concrete type of frost structure is formed in practically all soils which have been largely depleted of humus.

In the presence of humus, frost in the soil is usually of a porous structure.

A concrete type of frost structure is formed in heavily compacted soils, irrespective of the humus content.

A concrete type of frost structure frequently forms when frost penetrates below the humus layer. In lightly com-

pacted pastures and meadows this occurs usually at depths below 3 or 4 inches.

Depth of soil freezing is affected, in general, by most of the same factors that control the type of frost structure formed. This is to be expected, as the concrete type of frost is associated with deeper freezing, whereas the more porous types of frost are usually found if conditions favor shallow freezing.

Open lands tend to freeze more deeply than undisturbed forest lands. One major exception is the case of coniferous stands on poorly drained soils, which may freeze as deeply as open lands or more deeply. Hardwood stands consistently freeze to shallower depths than any other areas unless the litter and humus have been disturbed by fire, logging, or grazing.

A study in Connecticut disclosed that litter and duff of a mixed red pine and white pine plantation reduced frost penetration by 40 percent.

Another study carried on in the Northeast in 1939–1940 demonstrated the effect of removing the litter and humus. Paired plots were established among hardwoods and in a stand of white pine. On one of each pair of plots all the litter and duff were removed. The other plot was left undisturbed. In the hardwood plots without humus, frost was present almost continuously for the entire period of observation and reached a depth of nearly 3 inches. On the undisturbed plots, frost was observed on only 2 days, and then only a few tenths of an inch in depth. Frost penetration in the undisturbed plot of white pine was 3.5 inches deep by the end of the observation period; in the companion plot, where the humus had been removed, frost went 8 inches deep.

Snow, particularly light, new snow, has value as an insulator and tends to retard deep penetration of frost. Even when freezing was severe, 24 inches of snow has prevented frost penetration. At other times, in less severe weather, 12 to 18 inches of snow have prevented frost penetration. A number of observations have shown that even though frost penetration has started before the first snow, when snow depths have reached 18 to 24 inches further penetration has stopped. Hardwood forests in general develop about the most effective snow cover for retarding frost penetration. Wind movement in a hardwood forest is consistently low because of the retarding effect of the bare trunks and limbs; thus little drifting occurs, and the snow is distributed evenly over the soil surface. Hardwoods also intercept little snow as compared with conifers; therefore snow accumulation tends to be greater there than in coniferous stands. Bare fields, on the other hand, are frequently swept clean by winter winds, with the result that large areas are without a protective snow covering and are subject to deep penetration.

Persistence of concrete frost during rain or snowmelt periods, particularly in the spring, is important from a hydrologic standpoint. If such frost would always disappear before rain or snowmelt could produce surface runoff, it would have little significance.

Often soil freezing will start before the first snow accumulation and will continue until snow is deep enough to prevent further freezing of the soil. If the snow stays that deep or deeper, thawing will begin at the lower edge of the frozen zone of soil because an accumulation of heat rises toward the ground surface from warmer depths below. Soil frozen to a considerable depth can thaw under a snow cover of 30 or 40 inches. When the snow has disappeared, the frozen soil starts thawing from the top while continuing to thaw also at the bottom edge. Usually the last remnant of frost is found midway between the point of maximum penetration and the surface.

Frost seldom penetrates to uniform depths, even in places a few feet apart, because of the variability of the microphysical environment. The lack of uniformity is especially significant during a period of snowmelt. When frost is

thawing, the shallower depths of frost disappear first.

Studies in New England showed that the extent of frost in forested areas declined before or during the snowmelt period, but frost remained in nearly all open areas during the entire period of snowmelt.

Another study in south central New York, which covered entire subwatersheds ranging from 7 to 1,335 acres, disclosed no frost in three out of four wooded watersheds. Frost was present in a fourth watershed in only 12 percent of the area. Thus frost may occur only in parts of a watershed while the rest of the basin may be free of frost. Cultivated watersheds showed frost penetration everywhere at the beginning of the snowmelt period; the extent dropped to about 50 percent of the area by the end of the melt period. About 65 percent of pastured watersheds had a maximum of frost penetration but had no frost by the end of the snowmelt period.

In conclusion: Considerable changes in the type and extent of soil freezing may be brought about by changes in the way land is used and by the condition of vegetative cover. They in turn cause changes in infiltration, percolation, and runoff and have a vital bearing on floods in winter and spring.

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Fire on the Watersheds of the Nation

C. Allan Friedrich

Through the ages wildfire has periodically swept over large regions of the United States, denuding watersheds of their protective covering of vegetation and setting the stage for floods and erosion.

Wildfires had a significant part in causing the erosion in the headwaters that provided the extensive sediments which today are the fertile soils of the Mississippi Valley. Wildfire was largely responsible for maintaining prairie cover on thousands of acres along the eastern edge of the Great Plains, on land otherwise capable of sustaining a hardwood forest.

Some of the most valuable commercial forest stands in the western United States are believed to be the result of fire. Had it not been for the recurrence of fire in the forests of northern Idaho, for example, the famous white pine would long ago have been replaced by the less valuable but the more shade-tolerant western redcedar, western hemlock, and white fir. The fabulous Douglas-fir of western Washington and Oregon owes its abundance in part to fire, which has given it an advantage over the cedar and hemlock that otherwise would predominate on much of the land that is now occupied by Douglas-fir.

In the 19th century millions of acres of the United States were burned, purposely or carelessly, and other millions burned from natural causes without attracting much attention.

Fire was commonly used by the pioneers to clear forest and brushland for crops or forage.

Gradually the need for conservation of the forests and rangelands and the tremendous toll being taken each year by fire began to gain recognition. Fire was first condemned as a destroyer, but soon some of the relationships between fire and soil erosion and flooding were recognized and watershed protection was seen as another potent reason for fire prevention.

As more and more is being learned through research and experience about the relationships between vegetation, soil welfare, and streamflow, the preservation and improvement of watershed values are becoming the principal objective in the protection and management of many of the forest and range lands.

For many years Government agencies, in their campaign for fire prevention, had a tendency to condemn all fire as harmful and destructive. That approach did not ring true to some men in the West who had used fire to remove brush from grazing lands, sometimes with considerable success. The tradition of burning still persists in some parts of the country.

Finally it became clear to some conservationists that the need was great for more thorough knowledge concerning the effects of fire on vegetation and watershed values. Research was undertaken to determine if and how fire could be used as a tool for improved land management.

In 1932 the Intermountain Forest and Range Experiment Station began a series of experiments in the use of fire to control big sagebrush on deteriorated rangelands in southern Idaho. The resulting publication, Farmers' Bulletin 1948, *Sagebrush Burning—Good and Bad*, by Joseph F. Pechanec and George Stewart, gave recognition to the concept that under certain conditions the advantages to be gained by controlled burning could exceed the ill effects.

Subsequently in northern Idaho the Forest Service has undertaken research into the possibilities of using controlled fire in the fight against white pine blister rust. Controlled burning after logging is gaining acceptance in certain situations as a silvicultural practice to clean up undesirable species, to remove diseased or insect-infested trees, promote natural reproduction,

or facilitate seeding or planting of desired species. It is becoming a common practice in many western areas to burn wind-thrown timber and other flammable accumulations of fuel under chosen conditions, rather than to risk that wildfire will start in them.

THE RELATIONSHIP between watershed functions and fire is complicated and not completely understood, but some of the fundamentals have been established. The desired watershed function of the land, stated in simple terms, is to receive precipitation and dispose of it in an orderly way. A protecting cover of healthy vegetation and a generous layer of litter and humus on and in the surface soil are essential.

Fire kills or injures most types of plants and consumes part or all of the living plant cover, litter, and humus, thus leaving the surface of the soil bare. When that happens, severe runoff and erosion from intense rainfall might follow. As the raindrops beat upon the unprotected soil surface, the fine particles of soil and ash are stirred about and washed into the tiny spaces between the larger particles, soon making the soil surface practically impervious to water.

This is a common cause of the devastating flash floods that often follow forest fires in the mountains.

The surface runoff from burned areas also causes serious damage to the watershed itself. The water that runs off the surface obviously is not available in the soil to aid the recovery of the fire-weakened vegetation on the land. Besides robbing the plants of water, the surface runoff carries with it some plant nutrients in the ashes and surface soil, thus leaving the soil less fertile than before. The next generation of plants is handicapped in its ability to reclaim the area to its condition before the fire. In much the same way, wind erosion sometimes causes serious damage to burned-over watersheds by carrying away the nutrient-containing ashes, the little remaining humus, and topsoil from critical areas.

The time one watershed needs for complete recovery from a severe fire would be hard to determine. It may be measured in decades for grassland and brushland and in centuries for forest. Considerable progress has been made, however, as soon as enough cover of low vegetation has developed to protect the soil from the beating of the raindrops. That commonly requires one to several years on grass and brush lands, but some severely burned forest sites may be nearly barren for many years. As the protective covering develops, the surface soil gradually loosens up again through the action of insects, plant roots, wetting and drying, and freezing and thawing so that it gradually regains much of its former porosity. In the places where severe erosion has occurred, rebuilding the soil to its former depth and humus content is a long, slow process that is not even begun until the rate of erosion has declined below the rate of the soil-building processes.

Some conservationists tend to feel that recovery has been accomplished when the infiltration rate has improved to the extent that it exceeds the expected rate of rainfall. That is a desirable point in recovery, but it should not give an undue sense of security. Do not the frequent reports of record-breaking rainfall here and there indicate that even our longest weather records give us only a poor indication as to what kind of weather we should expect? It is generally the above-average storm that does the damage, and when the record-breaking rains occur even the maximum possible infiltration rates and water-holding capacities of our watersheds are none too great.

The seriousness of the damages caused by fire depends, not on whether the fire is planned or wild, but on several other important factors: The size and intensity of burn, soil characteristics, steepness of slope, amount and character of precipitation to which the burned area is subject following the fire, type of vegetation present

before the fire, length of time the soil will be bare before revegetation occurs, type and amount of vegetation that comes back after the burn, proportion of the watershed unit affected by the fire, characteristics of associated unburned portions of the watershed unit, and condition and adequacy of the stream channel to carry increased flows in an orderly manner.

Controlled or prescribed burning, properly planned and executed, seldom results in striking damage, because advantage is taken of favorable combinations of those factors. Planned burning should be done only to accomplish specific objectives and with adequate controls to keep the fire within desired bounds and under conditions of wind, humidity, and fuel moisture that will hold burning intensity to the minimum necessary to accomplish the objective. Repeated burning of the same area should be avoided. Burning should not be done on impervious, shallow, unstable, or highly erodible soils, or on steep slopes—especially in areas subject to heavy rains or rapid snowmelt. When existing vegetation is likely to be killed or seriously weakened by the fire, measures should be taken to assure prompt revegetation of the burned area. Burns should be limited to relatively small proportions of a watershed unit so that the stream channels will be able to carry any increased flows with a minimum of damage.

When burning is done under those conditions, the advantages gained in control of weeds or brush, improved silvicultural relations, reduced fire danger, or other ways may outweigh the limited damage done to watershed values. Fire should still be recognized, however, as a drastic and dangerous treatment and must be allowed only after careful weighing of all the values at stake gives reasonable assurance that burning is justified. Thinking people must not accept controlled burning on lands with high watershed values as a satisfactory practice, but must constantly be on the alert for safer ways to gain the desired goal.

Meanwhile, whenever controlled burning is contemplated, those responsible should always be sure that they are complying with local, State, and Federal regulations and should take full advantage of the best guidance available for the type of burning to be done. Assistance or guidance in the form of publications can frequently be obtained from local fire wardens, county agents, local offices of the State forestry or conservation departments, State extension service, Forest Service, Soil Conservation Service, Bureau of Land Management, and others.

Wildfires, or any poorly executed planned burning, are always dangerous and often very damaging. They always occur without regard to the factors that control their damage potential; often they occur under conditions that favor their spread. When that happens, the other factors, too, are likely to be at their worst. Millions of dollars are spent for the prevention and suppression of wildfires on the Nation's watersheds, and still many thousands of acres are ravaged by fire each year.

Some of the fires, by destroying the water-controlling ability of the watersheds, have been responsible for floods that have caused tragic loss of life and tremendous property damage. An example is the flood which struck La Crescenta, Calif., on December 31, 1933. It took 30 lives and did damage estimated at 5 million dollars. The flood arose primarily from recently burned parts of the watershed above. Unburned watersheds nearby handled the storm with little or no flooding.

Near Yucaipa, Calif., fire started on July 4, 1950, and burned some 630 acres of chaparral-covered foothills. On July 6, while mop-up crews were still on the fire, an intense thunder shower dumped about three-fourths inch of rain over the burn and surrounding area. The resulting flood blocked roads below with sediment and debris so that bulldozers were needed

to aid removal of the fire equipment. Several thousand dollars of damage was done by the floodwaters from the burned area, yet little or no water flowed from adjacent unburned drainages.

Fire on croplands is becoming less common each year as farmers learn the advantages of incorporating organic matter into the soil instead of burning it. Fall burning is especially undesirable, because it exposes the soil to wind and water erosion and to deep penetration by the concrete type of frost in winter.

Fire on grasslands does much more damage than is generally recognized. Fire, as it consumes the vegetation and litter, releases some of the stored plant nutrients in readily available form. When they are leached into the soil by gentle rain or snowmelt they sometimes promote lush and rapid regrowth of the unkilled plants or growth of new seedlings. The removal of the old vegetation by fire also tends to make any new green growth show up to better advantage than when it is partially hidden by old vegetation and litter. The especially lush, green appearance of grasslands after a fire, actually attributable to those two causes, is often wrongly interpreted to show that fire is in some way beneficial to the grass. The reduction in growth in succeeding years after the extra nutrients have been used up or washed away may go unnoticed.

Actually, fire kills or weakens many of the desirable forage plants. When heavy rains wash away the ashes and additional topsoil, thus robbing the plants of nutrients and water, damage is worse. Runoff from burned grasslands often heightens flood damages. Erosion once started on grasslands following a fire frequently continues for many years, even after the vegetation has recovered.

Many brushland fires are set each year in mistaken attempts to eradicate the brush in the hope that grass will increase. Although rather safe and effective methods have been developed for eradicating big sagebrush by fire in southern Idaho, that is not the case for many other undesirable kinds of brush and chaparral. Burning to control brush should not be attempted, except by thoroughly approved methods. To do otherwise is a useless waste of natural resources and time.

In California there are about 20 million acres of brushland or chaparral, most of which is of very little value except to protect the steep, erosive watershed lands. Yet millions of dollars are invested in equipment and facilities for fire prevention, detection, and control, and other millions are expended each year to control fires that do get started. These costs are justified by flood damages prevented.

The chaparral frequently makes considerable recovery in 3 or 4 years, but at least 40 years are required for the vegetation to regain maximum density. If severe erosion has occurred meanwhile, it doubtless takes much longer for the soil depth and water-holding capacity to be restored. Though the intensively developed and heavily populated valleys give watershed protection an especially high value in California, brush fires have much the same effect in other parts of the Nation as they have there and must be controlled wherever they occur.

Severe forest fires on high-value watershed lands represent just about the ultimate in destruction and waste. Such fires are even more serious than brush or chaparral fires. The effects last longer and are more complex.

Forests generally receive more precipitation than brush or grass lands, or they would not be in forest. Much of the forested mountain land in western Washington and Oregon and some in northern Idaho, western Montana, and northern California receive more than 60 inches of precipitation a year. In some places as much as 40 to 60 inches of water is stored in the snow pack on high, steep, mountain areas around the first of April each year.

Heavy rain on fire-damaged watersheds may result in severe flood damages in the valleys below.

The snow generally melts in 2 or 3 months; that means that the watersheds must handle water at the rate of 20 or 30 inches a month on the steep lands. In such situations the importance of the forest stand for water control cannot be overestimated.

At the Coweeta Hydrologic Laboratory in North Carolina cutting all vegetation from a heavily forested watershed and leaving the vegetation on the ground increased total runoff from the watershed by 17.29 inches the first year. The next year, because of water use by sprout growth and low vegetation, the increase was reduced to 13.35 inches. Though the situation is somewhat different in regard to a heavy burn on forest land, the figures give at least a rough idea of the possible increase in total runoff that may be expected following a forest fire.

Soil freezing is an important factor in soil-water relations in the northern half of the United States east of the Rocky Mountains. In that part of the country forest fires which remove the insulating cover of litter and humus promote soil freezing and development of a more impervious type of frost than is found in soils high in humus and protected by plant litter. Bare soils puddled by rain and then frozen may become practically waterproof, while protected soil high in humus, even though frozen hard, generally is not frozen solid and is still permeable to water. Spring rains that run off the surface of bare frozen ground frequently soak into and hasten the thawing of protected soil. Thus increased surface runoff, soil erosion, and flooding from snowmelt or winter and early spring rains are a common result of forest fires in areas where the soil usually freezes in the winter.

Snowfall accounts for most of the precipitation received on many of the heavily forested watershed lands in the Rocky Mountains, Sierra Nevadas, and Coast Range, where it often accumulates to great depths. The ground under those heavy snow packs is seldom frozen in snowmelt periods.

On larger burns, say of 50 to 100 acres or more, it is likely that somewhat more snow gets to the ground or snow pack than under the forest cover, largely because the unburned forest cover intercepts more of the snow before it reaches the ground. The magnitude of difference will depend on wind, temperature, and size and frequency of snowstorms. Cold, dry, snow, falling in large amounts and accompanied by wind, may mostly get to the ground, even through dense forest cover. Then the distribution will be rather even under the trees and drifted in the open burn, but the average amount reaching the ground may not be much different. But light falls of wet snow may be largely intercepted by the unburned trees and evaporated back to the air before the next storm, so that little of it ever gets to the ground. If this type of storm accounts for a large proportion of the snowfall, the amount reaching the ground may be considerably greater in the burn.

Whether it then accumulates to a heavy pack, melts, and soaks into the soil, or evaporates, depends on the weather between storms. On the average, however, the amount of snow reaching the ground in a large burn may not be very much greater than in a large unburned area.

Small burns within a large forested area often collect considerably more snow than the adjacent unburned areas. One explanation for this may be that the winds tend to move across the top of a forest much as they do across

the surface of a field, so that a depression such as is formed by a small burn tends to cause eddies in the wind currents, thus causing them to drop their load of snow into the openings.

Snow may generally be expected to melt somewhat earlier and more rapidly on burned than on similar, but unburned, forest land. The difference is more pronounced on south and west slopes in seasons of much sunshine. The snow may then disappear 1 to 3 weeks earlier on the burned areas. On north slopes and in seasons when the melt is strongly influenced by warm airmasses, accompanied by cloudy skies, the difference may be negligible. In either instance, the total runoff, if any, from melting by sunshine or warm airmass will be greater from the burned than from the unburned because of reduced interception and lack of available storage space in the soil.

When lots of sunshine induces appreciably earlier melting on burned-over than on unburned forest land the difference may be harmful or beneficial, as far as its effect upon streamflow is concerned. Melting generally is more rapid in the latter part of the season than early, because of longer days, hotter sun, warmer nights, the accumulation of heat-absorbing particles of dust and trash on the surface, and the aeration of the pack as sticks and stones begin to protrude. Therefore an early start may be beneficial in getting the snow off the burned area with the least disturbance. The early melting may tend to reduce the peak flow of streams by prolonging the melt, or it may have the opposite effect. For example: A fire that denudes the south slopes of a mostly timbered watershed might have a locally beneficial effect on the flow of the first stream. Further downstream, however, the early higher-than-normal flow from the burned area may coincide unfavorably with the normal peak flow from lower elevation or grass-covered drainages, to cause flooding there. Similarly, burning of the forest from a partially grass-covered watershed may result in local flooding if it causes melting on the formerly timbered portion to coincide with that on the grassland.

The warm airmass type of snowmelt, such as was largely responsible for the 1948 flood in the Columbia Basin, is most likely to occur late in the melt season. When, as in 1948, it follows a late spring in which the normal early-season melt did not occur, the results are likely to be disastrous. Warm airmass melting gains much of its danger from the fact that it is likely to continue day and night in open or shade on all aspects through a wide range of elevation. In contrast, sunshine melt stops at night, and allows for natural scheduling of runoff, because snow on south slopes at low elevations and on open land generally melts before that on north slopes, higher elevations, and shaded areas.

During warm airmass melting, the principal direct effect of fire is probably the contribution of an excessive amount of water from the burned area and the greater probability of surface runoff and erosion, especially if rains accompany the snowmelt. The excess water is greatest in the first year or two following the fire and gradually decreases as the use by vegetation increases.

Recovery of the watershed is a long slow process after a severe forest fire. Return of a protecting vegetative cover generally is fairly prompt in the hardwood forests of the East because trees and shrubs may sprout from the stumps or roots after a fire. Most coniferous trees, however, are killed by a hot fire. In fairly open stands, species of shrubs, weeds, and grasses may survive and provide a cover of sorts within a few years. But when some of the dense stands of tall conifers are killed, it often takes many years before even a low cover of grasses or weeds becomes established, because the seeds must come from beyond the burned area. If left to nature, recovery in such cases normally goes through several slow

stages of succession; first nothing but bare ground, snags, and erosion; then gradually mosses, weeds, grasses, and perhaps a few shrubs; gradually, the shrubs take over, with perhaps a few tree seedlings here and there; after many years the trees finally begin to crowd out the shrubs, but it takes 100 years or more for a tree to grow big and probably a couple of generations of trees before the soil depth lost by erosion has been replaced.

THE DESIRABLE PRACTICE of seeding or planting burned forest land to hasten recovery is gaining in popularity, but the annual burn will have to be greatly reduced and the planting rate multiplied before they will be in balance. Even if all burns could be replanted promptly, it still takes about a century to grow a tree.

Avalanches of snow or earth often occur on steep slopes following forest fires in the heavy snow country. Once avalanches get a slide path established they may occur annually or periodically for decades. When they dump their loads of rock, earth, and debris into a stream channel they may be a practically permanent source of channel instability and contribute greatly to flood damages. Even the natural creeping of fire-killed snags down steep slopes may be a significant factor in causing or maintaining unstable channel conditions for a half century or more following a fire. That is the situation in some of the northern Idaho and western Montana country that has been ravaged by big fires.

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The Management of Public Watersheds

G. R. Salmond and A. R. Croft

Nearly as old as the hills themselves is the thought that conditions on the hills influence streamflow, erosion, and sedimentation.

The ancient Chinese had a proverb: "To rule the mountain is to rule the river." No doubt it was rooted deep in centuries of Chinese experiences. But the Chinese did little about it; vast mountain areas in China are now a total waste and rivers are choked with sediment caused by the destructive force of water on the watersheds.

The Greek philosopher Plato about 400 B. C. spoke out with the clarity of a modern conservationist: "There are mountains in Attica which can now keep nothing but bees, but which were clothed, not so very long ago, with fine trees producing timber suitable for roofing the largest buildings, and roofs hewn from this timber are still in existence. There were also many lofty cultivated trees, while the country produced boundless pasture for cattle.

"The annual supply of rainfall was not lost, as it is at present, through being allowed to flow over a denuded surface to the sea, but was received by the country, in all its abundance—stored in impervious potter's earth—and so was able to discharge the drainage of the heights into the hollows, in the form of springs and rivers with an abundant volume and wide territorial distribution. The shrines that survive to the present day on the sites of extinct water supplies are evidence for the correctness of my present hypothesis."

George P. Marsh, the United States Ambassador to Italy in 1861, recognized the terrible destruction of the soil over past ages. Impressed by its consequences, he wrote a book, *The Earth as Modified by Human Action.* Citing about 400 examples, he concluded

that "the earth is becoming less and less inhabitable."

Regarding conditions in and around the once rich Roman Empire he said: "We shall find that more than one-half their whole extent . . . is either deserted by civilized man and surrendered to hopeless desolation or at least greatly reduced in both reproductiveness and population . . . Vast forests have disappeared . . . the soils of the Alpine pastures . . . are washed away; meadows, once fertilized by irrigation, are waste and unproductive."

Recognition of the consequences of destructive land use, one of which may have been the decline of some Old World civilizations, undoubtedly stimulated efforts in the New World to conserve the land and its resources.

THE NEED for providing more specific attention to the watershed aspects of land management to some extent has grown out of the research that shows how watersheds function and how their orderly function may be changed by use.

Watersheds convert large amounts of rain and snow to streamflow. For example, in places where 24 inches of precipitation annually reaches the soil, a plot only 10 feet square receives and disposes of about 6.25 tons of water each year. One acre receives 2,718 tons; and 10,000 acres, not a very large watershed, receives and disposes of more than 27,180,000 tons.

In the orderly disposition of those huge amounts of water, every piece of ground—a square foot, an acre, a square mile, a complete drainage basin—performs a vitally important hydrologic function. That that function can be changed by man's use of the land has been demonstrated in recent times by many experiments and experiences.

On the brush-covered mountains in southern California, extensive runoff and soil erosion on watershed slopes, and consequent debris-laden floods downstream frequently have followed in the train of forest fires. Two rainfalls in January 1954, totaling 6.0 and 13.0 inches, respectively, eroded on the average 0.6 inch of ash, soil, gravel, and decomposed rock from steep slopes burned a short time before. Sedimentation downstream was 28 times greater than from comparable unburned watersheds. Peak stream discharges from a 1,500-acre watershed only 32 percent burned were 67 times normal for dry soil conditions and 15 times normal for wet soil conditions.

Some erosion and runoff experiments were made in the Wasatch Mountains of Utah on a number of plots, each one-tenth of an acre, with aspen-herbaceous cover. The geologic evidence indicates that soil on the experimental sites has been substantially stable for the most part of 20,000 years. During the first 11 years of the experiment, 448 inches of precipitation fell as snow and rain, some of very high intensity. No soil was eroded, and only a trace of surface runoff occurred. Then all vegetation and litter were removed from half the plots. In the following 6 years, 271 inches of rain and snow fell. On denuded plots surface runoff—all from summer rains—was only 2.9 inches, about 1 percent of the total precipitation, but it was enough to erode about 200 cubic feet of rich black topsoil (almost enough to fill thirty 55-gallon barrels) from only 0.1 acre. The undisturbed plots continued to function as before.

PUBLICLY OWNED LANDS—Federal, State, and community—comprise more than one-fourth of the 1.9 billion acres in the continental United States. Most of them are rural lands and are important for watershed protection. Public lands include the highest water-yielding areas in the regions in which they are located. A large part of significant sediment-producing areas in the west are in public ownership. They are generally located upstream from major reservoirs constructed for irrigation, power, flood control, municipal supplies, and industrial uses. The character of the management of public lands

therefore vitally affects the sedimentation and duration of the useful life of a great part of the water developments in the Nation's rivers.

The Federal Government, through some 20 agencies, administers for various purposes more than 455 million acres of rural lands in the continental United States. Considered here are the classes of lands of very large acreage that are administered by the major land-managing agencies in the Department of Agriculture and the Department of the Interior.

The national forests comprise about 161 million acres and are under the administration of the Forest Service of the United States Department of Agriculture. With some exceptions, principally in the Lake States, the forests are largely mountain watersheds that supply most of the water for the semiarid valleys of the West and in the East are situated on the headwaters of many of the major rivers. Although the national forests make up only 21 percent of area of the 11 Western States, they furnish about 53 percent of total annual runoff. National forests in the West yield an average of about 14.0 inches of water annually, compared to about 3.3 inches for other lands of lower elevation.

Watershed lands administered by the United States Department of the Interior include more than 264 million acres under the supervision of the Bureau of Land Management, Indian Service, National Park Service, Fish and Wildlife Service, and Bureau of Reclamation. The Bureau of Land Management and the Indian Service have charge of some 179 million acres and 57 million acres, respectively. The lands are mostly in low-rainfall regions of the semiarid West, and therefore water yield is relatively low. Nevertheless some of them produce relatively large amounts of sediment because storms of a "cloudburst" type lash areas that have sparse natural cover or whose cover was ruined by unregulated use before the Taylor Grazing Act was adopted in 1934.

Lands administered by the National Park Service consist of about 14 million acres in 172 national parks, monuments, and other tracts of national interest. They are administered as provided by law on the principle of "inviolate protection," which directs that no resources will be consumed or features destroyed by lumbering, grazing, mining, hunting, or other uses. A large part of the land administered by the National Park Service is in high, rugged mountain areas, which are important sources of water. The remaining 14 million acres of Department of the Interior lands are included in reclamation projects and wildlife refuges.

Lands in State ownership include approximately 80.3 million acres. About 1 million acres are reserved for institutional sites. Much of the remainder is so situated that it has significant watershed values. Included in this group are 14 million acres of organized State forests; 2.4 million acres of State parks; 4.8 million acres of wildlife reserves; and 57.9 million acres of State-grant and tax-forfeited lands, which are used largely for grazing and some farming.

About 3,100 community forests in the United States include some 4.4 million acres of land. Most of them are maintained for recreation and production of timber. Of more than 1,100 municipal forests, about one-third are maintained for watershed protection on the land from which municipalities obtain their water supplies. The management and use of other resources on them must be conducted so as not to interfere with the primary purpose of the community watershed.

THE ORIGIN of watershed management on publicly owned lands in the United States was the result of stimulation given the movement by a few leaders in conservation more than 75 years ago. Progress since is the result of action by communities, the States, and the Federal Government.

The development of community forests is one of the most significant

features of public land management in the Nation today because they were established locally by the people to meet a common need. Community forests for wood products and recreation and probably also for water were established before the States or Federal Government became actively interested in problems of land management.

Interest by the States in forest management extends far back. Massachusetts, in 1837, was the first State to adopt legislation authorizing a survey of forest conditions. Michigan and Wisconsin did so in 1867. Action for land management by the States in the interest of watershed protection was apparently stimulated by a memorial from the American Association for the Advancement of Science to the Congress and the State legislatures in 1874. The memorial directed attention to the exhaustion of timber and to the need for management of our forests to conserve the timber and water resources. The American Forestry Congress in 1886 advocated that Federal lands at stream sources be granted to the States to be kept and held in perpetuity for the public use with a view to maintaining and preserving a full supply of water in all rivers and streams.

New York took the earliest action in land management in the interest of water. In 1868 a Commission of Fisheries was established to look into destruction of forest cover, which appeared to have caused pollution of water to the detriment of fish. State lands were withdrawn from sale in 1883. In 1885 a Forest Commission was established to organize and manage the State forest land for the primary purpose of protecting water supplies. All State lands were placed under the protection of a constitutional amendment, which prohibited cutting of timber and provided that the newly created forest preserve be kept forever in wild condition. The forest preserve has grown from about 685,000 acres to about 2.4 million acres. Legislation was enacted also to authorize purchase of lands outside the forest preserve for the "maintenance thereon of forests for watershed protection, production of timber and other forest products, and recreation and kindred purposes."

Colorado was the first State to make provision for management of forest land through a clause in the State constitution, which directed the State legislature to provide for protection and management of State-owned forest land. Irritated by the Federal public-land disposal policy and destructive use of Federal land in Colorado, the State Constitutional Convention in 1876 asked the Congress to give control of Federal forest lands to the States in regions where irrigation is necessary, to prevent injury to Colorado, and to avoid damage which would "bring destruction and calamity upon the entire population of the so-called far West."

The California State Board of Forestry, organized in 1885, urged in its first report that all Federal and State timberlands not suitable for agriculture be permanently reserved and put in charge of forestry officers. In 1888 the State legislature asked Congress to stop disposal of Federal lands in California and preserve them permanently for protection of watersheds.

In Utah, although the State took no early action to get land management in the interest of water either on its own or Federal lands, the people did. About the turn of the century several towns made appeals to the Federal Government for protection from floods originating on damaged Federal lands. As the result of devastating floods at Manti, Utah, largely from Federal lands, the people memorialized the Congress in 1903 for the purpose of placing their watershed under management in the interest of flood prevention. Soon thereafter the Manti Forest was created.

During the yearly activity by the States, the Federal Government made only feeble gestures, or none at all, to correct its destructive land-use policy. Secretary of the Interior Carl Schurz, during his term of office from 1877 to

1881, repeatedly urged reservation and conservative management of federally owned lands, but the Federal Government could not be aroused from its lethargy. Finally, in 1891, largely at the insistence of Secretary of the Interior Noble, a rider was attached to an act amending the land laws that authorized the President to establish forest reserves from the public domain. Interest in protecting the water, as well as the timber resource was behind this action. Chief Forester Gifford Pinchot called this law "the most important legislation in the history of forestry in America."

Watershed management on Federal land is largely an outgrowth of the act of June 4, 1897. The act provided that "no public forest reservation shall be established except to improve and protect the forest within the reservation, or for the purpose of securing favorable conditions of water flows or to furnish continuous supply of timber." The Weeks Law of March 1, 1911, provided for purchase of land "for the protection of watersheds of navigable streams," thus authorizing the Federal Government to extend its ownership in important watersheds to areas outside of the public domain.

Another monumental event in the development of land-management policy was a letter from Secretary of Agriculture James Wilson to Gifford Pinchot in 1905, when the forest reserves were transferred to the Department of Agriculture and renamed national forests. In directing the Chief Forester to "see to it that the water, wood and forage of the reserves are managed to assure the greatest good to the greatest number of people in the long run," the letter established the fundamental policy that has guided multiple land-use management of national forest lands.

THE PRACTICE of watershed management on publicly owned land has been done by applying three general methods: Multiple land use, protection or closure of areas to land uses, and experimental management in the interest of water yield.

Multiple land use on Federal lands is the method of management which has given recognition to water along with other resources on millions of acres. Coordination is the keynote of the multiple-use principle, each resource being developed and used as fully as possible without undue interference with other resources. The initial job of integrating watershed management with other land-use activities was not easy. Timber cutting and grazing without benefit of management, and much of it free, prevailed on public lands in the early development of the country. Such use was widespread before withdrawal of Federal lands for watershed purposes was recognized as a sound national policy.

Following withdrawal, the earliest consideration, given broadly, to watershed management was through efforts to use the land primarily for timber production and grazing with the thought in mind that conservative use would provide needed protection to the water resource.

Land management in the interest of the water resource has been much improved in the past half century on Federal land, particularly in conjunction with timber harvesting and forage utilization. In selling timber it is now customary to include stipulations in sale contracts for the purpose of protecting watershed values. Examples are layout plans and construction standards for roads and skid trails designed to minimize erosion and surface runoff; control of logging methods to reduce ground disturbance; limitations on operations adjacent to streams; and required use of planting, seeding, and small structures to control erosion and runoff after logging on areas of disturbed soil.

Grazing also is being managed so as to improve and maintain the range resource and provide adequate cover to prevent rainstorm runoff and erosion of soil. The thinking is that sufficient vegetation must be left on grazed

areas each year to maintain soil stability and that only vegetation not needed for that purpose is available for grazing. Grazing is stopped temporarily in some localities to restore satisfactory watershed conditions and to protect restorative range and watershed improvements on badly deteriorated lands.

Construction activities also are done under specifications aimed at preventing erosion and flood runoff. These activities include road planning and construction, right-of-way clearing for utility lines, mining activities, and other uses that disturb the surface.

Other types of work which are done on Federal lands to benefit or make better use of water resources include water spreading, terracing for erosion control, stabilizing stream banks and channels, and controlling gullies with structures and vegetation.

No single activity has been more important to watershed management than the development of fire protection. Fire protection has increased tremendously in effectiveness on public lands since 1900. It has prevented widespread destruction of watershed cover and topsoil and the consequent damages from erosion, floods, sedimentation, and water pollution, which stem from such destruction.

Even though there has been substantial improvement in multiple-use land management in the past few decades, watershed conditions are still unsatisfactory on part of our Federal lands. Some lands are still on the downgrade, and damage to land through excessive logging, grazing, and fire, which occurred before the present regulatory laws, has not been corrected.

Most State lands are used for multiple purposes, although management of parks and wildlife reserves stress a primary purpose. Multiple-use management on State lands presents a variety of conditions, varying from good to unsatisfactory from a watershed viewpoint. Fire protection on State forests is generally good. On State forests maintenance of forest cover for watershed protection is generally recognized as an essential part of forest management, and watershed management is being given increased attention. Some other State lands, particularly in the West, however, receive little or no protection or management, are in poor condition, and are damaged by accelerated runoff and erosion. Lack of funds and scattered ownerships contribute to the difficulties of the managers of State lands.

Closure means the prohibition of all, or nearly all, normal uses in order to avoid damaging the quality of the water resource.

The total area to which closures are applied is not great, but substantial acreages are included in closed watersheds, mainly to protect community water supplies. Examples are the watersheds supplying the cities of Colorado Springs, Colo.; Santa Fe, N. Mex.; and Portland, Oreg.

Many persons believe that modern water-treatment facilities are such that complete closure should be necessary only infrequently to protect the quality of water resources. Many watersheds, where closure is impossible because of the landownership pattern, provide satisfactory municipal supplies. In others, limited use is permitted.

On the 91,000-acre Cedar River municipal watershed of Seattle, Wash., extensive logging is permitted on the city's lands, which constitute about three-fourths of the watershed, and in the adjacent national forest lands. Entry by the public is prohibited. A special commission's report in 1944 recommended controlled use of the watershed, with its collateral timber production values, rather than complete protection.

Springfield, Ill., has a 4,300-acre municipal watershed, which provides water and electric power to the city and also yields an annual income of about 50,000 dollars from recreational and residential use. A crop of timber is also developing.

Newark, N. J., has a city watershed

of 41,000 acres—a valuable forest from which a small income is obtained from timber without impairing the yield of water.

The watershed of Corvallis, Oreg., includes 8,910 acres. More than half of it is national forest and nearly all of the rest is owned by the city. Since 1920 logging had been prohibited. After 1945 or so proposals to develop the area with roads to harvest the timber under a sustained-yield program met strong opposition. But later a large volume of mature and overmature timber was uprooted by winter storms. The down timber and dry summers created ideal conditions for an epidemic of bark beetles, which killed much green timber. In 1952 it became apparent that action was needed to reduce the fire hazard, recover some of the loss in the sawtimber, develop roads to assist in halting future epidemics, and protect watershed values by regenerating a vigorous forest cover in the affected areas. The city and the Forest Service cooperated in developing a plan for undertaking timber operations.

But proper attention to all watershed resources was complicated at that stage. The work of building roads, which normally would have extended over 15 or 20 years, now had to be accomplished in less than 5 years to be effective in controlling the insect infestation and reducing the fire hazard. Special sanitation measures also were required because of the extensive operations scattered over the entire watershed. Silvicultural methods had to be modified to meet the emergency. Problems arising from herds of deer in and around the clear-cut areas appeared likely, with the chance that they might hamper the establishment of Douglas-fir reproduction by trampling and browsing. The watershed is a game preserve, and evidence of overbrowsing and soil movement near streams was noted.

Observations late in 1954 indicated that the timber operations on the Corvallis watershed were effective in meeting the emergency resulting from the insect infestation, but the long-range effects on the watershed could not be appraised that soon. In any event, the watershed provides an interesting case history which will permit appraisal of the relative merits of prohibiting or permitting timber operations in a municipal watershed.

Closure will always be an important watershed management measure on some critical areas, such as steep slopes, where any use at all causes serious soil disturbance. It will be necessary also for limited periods to help in restoring damaged areas to usefulness.

A third method of watershed management, primarily to enhance the yield of water, is in the experimental stage. The method emphasizes control of vegetation. Research in the Southeast and Intermountain Region has shown that summer streamflow can be increased by control of vegetation along streambanks. Experiments have demonstrated that repeated cutting of the forest cover under certain conditions may result in a substantial increase in streamflow. In the Rocky Mountains experiments have been started to determine the effect on snow accumulation and streamflow of timber cutting in high areas of deep snow pack. Those and other research activities hold promise for more intensive watershed management in the future.

Outstanding watershed needs have been summarized by the American Forestry Association. They include:

A nationwide inventory of areas that are sources of water, with special reference to the amounts, rates, and qualities of waterflow and the types, extent, and values of water use.

Classification of watershed forests in terms of their requirements and values for the highest water production, erosion prevention, and flood and sediment damage abatement.

Application of measures to protect and manage forests, designed to maxi-

mize the contributions for a given set of conditions, with regard to the requirements for timber, recreation, and other forest products and services.

Intensified and more widespread application of measures to improve soil and waterflow to forested and other parts of damaged watersheds.

The statement applies particularly to forest lands, but it is applicable also in large part to rangelands.

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In some parts of the country, as at Upland, California, the welfare of highly developed communities is closely related to watershed conditions on nearby mountains.

The Yazoo-Little Tallahatchie Flood Prevention Project

William L. Heard and
Victor B. MacNaughton

One hundred million tons of soil have been stripped from the hills each year in the Yazoo-Little Tallahatchie Watershed in northwest Mississippi. Ten or fifteen floods have inundated one-fifth of the land each year. The annual damages from floods and sediment have exceeded 4.5 million dollars. You see how great are the land problems in the basin, which covers about one-fifth of Mississippi.

The entire watershed comprises some 5.7 million acres. The western 1.5 million acres are a level alluvial plain, a part of the fertile bottom lands of the Mississippi Delta. The remaining 4.2 million acres of undulating or hilly uplands comprise the province of the Yazoo-Little Tallahatchie Flood Prevention Project. The uplands are drained by four major tributaries—the Coldwater, Tallahatchie, Yocona, and Yalobusha Rivers.

The degree of erosion varies by major soil areas, which lie in successive belts that extend the full length of the watershed. Along the extreme eastern border lies the Pontotoc Ridge, a band of red, sandy clay that is fairly resistant to erosion but is underlain by deep sands of lower resistance. To the west is the Flatwoods area of heavy clay soils, resistant to gully erosion. Next is the Clay Hills section of upper Coastal Plains materials, overlain by shallow to moderately deep loess, which is subject to severe sheet erosion and moderate gullying. The remainder of the uplands, the Brown Loam area, is moderately deep to deep loess over deep sand or mixed sand, clay, and gravel. Here much land has been virtually destroyed by gully erosion; roadbank erosion is severe; and along the western bluffs stream erosion is spectacular.

Forest lands aggregate about half of the 4.2 million acres of upland area. Some 85 percent of the forest land is in small private ownership, primarily in farm woodlands. As little or no proper forest management has been exercised, the timber stands have been reduced to a preponderance of small, defective trees of little value. Uncontrolled fires and grazing have destroyed much of the ground cover and have been partly responsible for the fact that roughly two-thirds of the forest land supports stands of less than 300 board-feet to the acre. The average annual growth per acre is only 62 board-feet, less than one-fifth of the potential. Exceptions to these general forest conditions are lands of the Holly Springs National Forest and the Land Utilization Project No. 21, which display the improvement possible by less than two decades of fire control and improved management.

Croplands and pastures also reflect past land use and abuse. Cotton, with its clean-tilled system of cultivation, was a prime factor in bringing land deterioration and economic deterioration to this area. Cultivation and subsequent abandonment of hillside acres to the ravages of erosion plus burning and overgrazing of grasslands have vastly increased runoff and sedimentation. As a result, some 255,000 acres were subject to a critical erosion in 1955. Not only are they unfit for any use; the sterile sand pouring out of them chokes stream channels and is deposited by floodwaters over once fertile bottomland fields. The infiltration capacity of the soil has been so reduced that in some of the minor tributaries less than 1 inch of rainfall causes minor floods. Even normal rainfall causes 10 or 15 floods each year and flushes millions of tons of sand into the valleys.

The economic conditions within the upland section reflect the general land conditions. In the early 1940's, when the survey report on the Yazoo Watershed was made, there were some 36,000 farm families with a net cash

income of less than 500 dollars a year. Thirty-eight percent of all farms were mortgaged for an average of 42 percent of their total value. Having limited cash resources, the rural people generally lacked adequate medical attention, simple sanitary facilities, and balanced diets. Low cash income also precluded the purchase of fertilizer necessary for the proper rotation and crop development and prevented the installation and maintenance of soil-conservation improvements. The high population (112 per square mile of cropland) and the lack of industries, which might have supplied or supplemented income, combined to exert still more pressure on the overworked land.

THE FIRST REMEDIAL ACTION was authorized in 1936. The Corps of Engineers undertook a comprehensive headwater project, based primarily on construction of four large floodwater detention dams and on channel enlargement and straightening of main stream channels below the dams. The principal elements of the program have been completed. All the dams have been constructed and much of the needed channel improvement has been completed.

The Yazoo-Little Tallahatchie Flood Prevention Project, an intensive erosion- and flood-control land-treatment program, was jointly undertaken in 1946 by the Soil Conservation Service and the Forest Service. Local leadership was provided by soil conservation district commissioners of the counties.

Its four major objectives are: The correction of land abuse, reduction in number and in duration of tributary overflows, reduction of sedimentation, and stream stabilization.

Activities under the coordinated program can be grouped into three major categories: Land-use adjustment, land treatment, and channel development, including stream stabilization.

LAND-USE ADJUSTMENT is a key phase of the overall program. The best use for each tract is determined on the basis of its capabilities. Cultivated crops are restricted generally to relatively level fertile bottom lands. Moderate slopes are designated for use as pasture or for restricted cultivation with proper conservation measures. Steep slopes and ridge tops are generally assigned for forest use. The best permanent agricultural use is assigned each acre to obtain maximum overall production and to minimize soil and water losses.

Plans have been prepared and the proper use has been designated for approximately one million acres on some 6,500 farms in the watershed. Conversion to proper use has been taking place at an encouraging rate. More than 45,000 acres of idle or gullied land and steep cropland have been converted to use as woodland since 1947. An additional 45,000 acres has been converted from idle land and steep, eroding cropland to perennial grasses or legumes as a result of the watershed activities.

LAND TREATMENT is aimed at land rehabilitation to reduce surface runoff, erosion, and sedimentation and to increase productivity. Equal emphasis is given treatment of cropland, pasture, and forest land.

Acceptance and application of some desired improvement measures have been slow on croplands. The traditions attached to the production of a clean-tilled crop, such as cotton or corn, have not been overcome. Rotations that combine alternate use of grasses or perennial legumes in the cropping system have been adopted slowly. In contrast, the cultivation of open-tilled crops on the contour, or with soil- and water-conserving row arrangements, has been generally accepted. Supporting measures, such as terraces and waterways, also have been put into fairly wide use.

Already 228,000 acres of the total 837,405 acres of cropland in the watershed are being properly managed with application of such conservation meas-

ures. Approximately 80,000 acres of cropland have been terraced, requiring the establishment of 2,100 acres of field waterways. Most of the 400,000 acres of hill cropland are farmed on the contour. Winter cover crops are planted annually on more than 25,000 acres. A type of rotation is being followed on 225,000 acres of cropland, which, although not always adequate, indicates a trend away from the continuous single-cropping system.

The improvement and development of pastures have been encouraging. A strong trend toward grassland farming and cattle raising has developed. Especially in the highly erodible Brown Loam section of the watershed, the use of steep slopes formerly idle or in crops has been greatly improved; large areas are now devoted to pasture or are producing forage from such plants as sericea lespedeza or kudzu. Commendable progress also has been made in improving depleted pastures and in other forms of pasture improvement. Approximately 111,800 acres of pasture have been improved since 1947. Of this, 84,000 acres have been seeded and fertilized. More than 2,200 stock water ponds have been constructed.

FOREST-LAND TREATMENTS include fire control, revegetation of denuded abandoned lands best suited for forest use, reinforcement planting in the understocked stands, and timber stand improvement and management.

Of all remedial measures, control of fires is undoubtedly the most effective contribution to flood control from a standpoint of influence on total water runoff. Elimination of wildfires improves conditions that enhance the water-absorbing capacity of the soil, facilitates the establishment of good vegetative cover, and makes possible improvement of overall hydrologic conditions.

All except three counties in the watershed in 1954 were under organized protection afforded by the Mississippi Forestry Commission with Federal financial assistance, as authorized by the Clark-McNary Act. Legislation was passed to bring the remaining areas under protection. While the desired goal of 0.5 percent has not been reached, the present average annual burn of 1 to 2 percent of the protected area indicates progress. The average area burned annually in unprotected counties is 20 to 40 percent of the forest land.

Although the tree planting program is one of the largest in the Nation, the revegetation job here has hardly begun. An estimated 200,000 acres of eroding lands needed planting with trees in 1954. In addition, an estimated 500,000 acres of depleted understocked forest stands must be interplanted to provide adequate protective watershed cover.

More than 64,000 acres have been planted. With its rapid growth and abundant needle cast, loblolly pine has proved to be one of the best gully stabilizers. Civilian Conservation Corps plantings made in gullies in 1939 leave no doubt that trees can heal eroded lands. The soil there is covered with a thick mat of pine needles. The stands were ready for a light cut in 1954.

Management of forest lands must be improved to restore timber productivity and watershed values of the 2 million acres of existing forest and to protect investments in the 250,000 acres of new forest built by revegetation of abandoned wornout lands.

The big job in management on the project is to get fully stocked stands of desirable species. On the upper slopes and ridge tops, that means work on an estimated 400,000 acres. Planting of pine seedlings, followed by release, is the only way desirable stocking can be obtained there. As the numerous and extensive pine plantations mature, there will be the task of thinning and managing them properly.

On the lower slopes and bottom lands, release cuttings are needed on some 500,000 acres. Desirable reproduction is sometimes present, but often an overstory of defective, low-grade hardwoods has to be removed.

Participation in forestry practices has been given impetus by the incentive payments for planting and timber stand improvement under the agricultural conservation stabilization program. Landowners in 1954 planted some 16 million pine seedlings on the Yazoo Watershed.

Surveys revealed the importance of remedial measures on forest land. For example, runoff from pine forests at the time of the survey was seven times greater than that from similar pine stands that were protected from fire, grazing, and overcutting.

CHANNEL IMPROVEMENT is an important adjunct to land-use adjustment and treatment on the watershed. As originally authorized by the Congress, an intensive program of land adjustment and treatment formed the entire basis for correction of watershed problems. As experience was gained, however, people learned that for a progressive program additional remedial measures would be needed. Channel work is an example of the need.

Channel improvement, wisely used with land treatment, reduces the peak discharges of streams and shortens the duration of overflows on valley lands when flooding does occur. Significant progress has been made on the Yazoo in rectifying stream channels. A number of large projects were completed.

An example is the work completed on the channels of the Tallahatchie Watershed. In the initial stages of overall planning, a major problem was to protect and develop the 84,000 acres of fertile valley in the upper part of the watershed, one-half of which was inundated as often as 10 times a year. A priority of operations was set up to encompass the objectives in their proper relationship.

The channels were developed in 1912–1915. For about 20 years most of them functioned satisfactorily, but because an increasing amount of sand deposited in the channel and perhaps because of other factors overflows became frequent, and their frequency and duration finally threatened the agricultural life of that area.

A study of the problem disclosed that in the 10 years from 1939 to 1950 there were 88 overflows at Etta, a gaging station near the Union-Lafayette County line. Forty-one of the overflows came during the crop season, May through September, and damaged crops. The overflows lasted 1 to 10 days. Upstream, where the channel had deteriorated further, the frequency of overflows was considerably greater.

Cleaning the channel and removing the extensive sand deposits and vegetation, with a nominal amount of enlargement, has reduced the average number of damaging overflows at that point from four a year during the crop season to only one.

To finance and maintain the improvements, the reactivation and reorganization by local leaders of a number of drainage districts was necessary. Approximately one-half the actual cost of the projects was at local expense. In one project, the local cost was more than 175,000 dollars—an indication that if local interests understand and accept the objectives of large projects, they will pay a significant share of the costs.

The projects have also highlighted an important question: "What degree of protection of valley land is economically sound and desirable to the local interests?" It has become evident, as other approaches are considered in connection with the objective of reducing floods, that the degree of protection varies with conditions and people.

An initial effort has been started in connection with the use of floodwater-retarding dams in carrying out this aim. The costs of rights-of-way or the limited benefits generally have limited the application of this approach, although in many situations in the watershed this method of treatment may be used when the landowners become aware of its advantages.

SEVERAL STREAMBANK stabilization projects have been installed in an effort

to develop methods of stabilizing the numerous head cuttings and meandering streams. The successful installation of work of this kind involves the development of criteria for coping with tremendous discharge of runoff under high velocity and the formation of organizations to help finance or maintain them. Much work remains.

A considerable success has been achieved in the stabilization of small, meandering streams primarily through the use of post-retards, or double lines of creosoted piling driven along strategic bends and tied together with hog wire interwoven to form a 6-foot mechanical barrier, which hastens the growth of plantings along the toe of the caving banks. Willow, cottonwood, sycamore, and kudzu are used.

PROJECT ORGANIZATION and planning procedures used in initiating the Yazoo program might provide helpful guides to leaders in other localities faced with similar problems. The Yazoo program is a program in which Federal, State, and local agencies cooperate with private landowners to reach various objectives in a particular section of the watershed. The size of the program made necessary the division of the watershed into small units so that untrained leaders and workers could visualize their part of the job.

The Soil Conservation Service maintains a technical staff consisting of a soil scientist, soil conservationist, civil engineer, and forester, under the guidance of an officer who supervises the work of the technicians and aids in planning the program and carrying out its operations. The staffs of area conservationists were enlarged to include engineering parties and work-unit staffs of farm planners and aids. The Forest Service maintains a force of 15 foresters, who work within the framework of the Soil Conservation Service plans. Another forester is assigned the task of carrying out the forestry phase of the subwatershed planning. Direct supervision of the forestry work is provided by a project manager attached to the staff of the Mississippi forest supervisor for the Forest Service.

When a landowner indicates that he is ready to participate in the watershed work, the Soil Conservation Service planner assists him in determining the needs of his land, with emphasis on those that will accelerate the watershed objectives. The help is given through the governing board of the soil conservation district, and the determinations are included in a district farm plan. The determinations include those needed for the entire farm.

The Forest Service technician is responsible for technical assistance in the application of the forestry practices. The Soil Conservation Service planner is responsible for the open land practices and the engineering practices. Thus the farm plan becomes an operations guide for landowners and agency representatives alike and provides the basis for longtime land-use adjustments needed on the farm.

A close working relationship has been developed among the agencies of the Department of Agriculture and the Vicksburg district office of the Corps of Engineers.

AFTER PRELIMINARY CONFERENCES on stream channel improvements, the Soil Conservation Service, at the request of the Corps of Engineers, prepared a land-use capability map and land-use pattern map, as a basis for the use of all of the lands under the jurisdiction of the Engineers adjacent to the four large reservoirs. District farm plans were prepared by technicians of the Soil Conservation Service on all lands leased by the Engineers to private landowners for agricultural use. The plans include measures that contribute to the objectives of the watershed program. Technicians of the Corps of Engineers assist the lessees in carrying out their farm plans.

The Corps of Engineers, in accordance with the overall land-use plan, planted more than six million pine seedlings on eroding or idle land.

The entire watershed was originally divided into 234 local or minor watersheds. The smaller ones were regrouped into 56 subwatersheds. The determination of the specific needs and programs for each of the subwatersheds should be finished by 1962. Completion of the entire project has been set for 1970. Technicians of the Soil Conservation Service and the Forest Service take the lead in determining the needs in each of the subwatersheds. Using data from soil surveys, aerial photographs, and other materials, land-use pattern maps are prepared as the basis for determining the flood control and conservation needs of the subwatersheds. Agreement is reached with local groups regarding program requirements.

This forms the basis of the work plan and the action program.

A work plan outlines the program for each watershed. Because of the wide variations in conditions and problems, the objectives may vary considerably between subwatersheds. It also outlines the procedures to be followed and assigns responsibilities among agencies and landowners for cost-sharing and maintenance. Scheduling of each phase of the program in proper relationship to other jobs or practices is included.

Primary responsibility for leadership in the program is placed on the commissioners of soil conservation districts. Federal assistance is provided through the soil conservation districts.

When the work plan is completed and funds are made available in a specific watershed, operations are begun in the district in which the subwatershed is located, or operations in the district are expanded to include the new subwatershed.

A coordinated effort is undertaken to acquaint all the people and agencies with the objectives, their responsibilities, and the need for cooperation. Throughout the watershed, soil conservation district commissioners have sponsored the organization of watershed associations, or steering committees, in order that the leader of the subwatershed may be well informed about the needed changes in land use and the engineering projects.

In order to bring the needs and interests of the landowner fully into the whole flood-prevention operations, he is helped to prepare a flood-prevention conservation farm plan, which represents his understanding as to the part he is to carry out in achieving the land use, erosion control, or other work, on his land. It also represents the part the district, with assistance from any source, is to have in carrying out the objectives. The maximum participation of the landowner is encouraged to the end that he appreciates and understands his responsibilities to his land and to his neighbors.

Materials and services are available to aid the district cooperator in carrying out key practices that contribute to the objectives. They are in the form of grants to the soil conservation districts and are adjusted so as to require an approximately equal contribution from the landowner in the same practices or others. The use of the grants is supervised by Soil Conservation Service or Forest Service technicians, to insure that the most effective use is made of the available materials or services.

Gully plugs or larger desilting basins frequently are required and built by the Government on a contract basis to supplement the vegetative treatment.

Such problems as roadside erosion and simple streambank stabilization problems generally are handled on a similar basis as critical erosion plantings. The county boards of supervisors or the State highway department assume responsibility for the work on roadside erosion stabilization. Landowners, informal groups, or drainage districts assume the responsibility for streambank stabilization work.

THE ROAD BACK to good land health and general prosperity for the Yazoo Watershed is a difficult one. Successful completion and maintenance of the remedial measures will require faith,

vision, and hard work by the landowners. The possibilities are exciting.

With the reduction in flood damage on bottom lands, future crop yields will be higher. Deposition of sterile sand on fertile fields will no longer be a constant threat. Improved farming practices will result in more production on less cropland. Diversified agricultural programs will enable little farmers to change from cotton.

Control of gullies will reduce the sedimentation problem. Stream channels will again carry their normal flow of water. Control of fire and grazing will reduce runoff and increase ground water storage. More usable water will be available for irrigation and industrial use.

Good land use will result in a more stable landownership, a higher standard of living, and an increased income. More industries in the watershed will reduce the pressure on the land. In turn the improved land and water conditions will make the watershed more attractive to new industries.

Well-stocked stands of timber protected from fires and grazing will mean a stabilized lumber and pulp industry. The improved soil cover on the forest land will reduce runoff. It is estimated that under good management the forest lands of the Yazoo Watershed can produce 300 board-feet an acre a year—a total of 600 million board-feet every year. Converted into stumpage value and man-days of work, the total impact on the local economy is not hard to visualize.

In the field of recreation the opportunities offered by four great reservoirs are unlimited. They are situated on the Mississippi flyway, and sportsmen will come to the watershed for duck hunting and fishing. An increasing population and nearness to the metropolitan area of Memphis may mean the development of summer camps, fishing, boating, and tourist trade.

Perhaps the big lesson to be learned from the Yazoo Watershed is not merely how a stricken land may be healed and local economy revived but how other watersheds can be prevented from reaching such a condition. The road back is never an easy one.

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A New Song on the Muddy Chattahoochee

Frank A. Albert and Albert H. Spector

Records from five of the larger waterworks in Georgia all tell the same story—a steady downward trend in the turbidity, or muddiness, of the water that is being pumped from the rivers for treatment at the filter plants.

What has been done to bring about this improvement at the plants in Atlanta, Augusta, Columbus, Macon, and Milledgeville?

They get most of their water from four rivers, which drain lands of widely varied soils and physical features.

Five factors affect the amount of soil that moves out of place in a watershed—the way land is used, the frequency and intensity of rains, the length of the growing season, the slope of the land, and the qualities of the soil. Only the first two vary enough on a watershed over the years to result in significant changes. For an answer, we must look to the hills; what has been

done in the hills above Atlanta will typify developments in the other watersheds.

THE CHATTAHOOCHEE RIVER is the main source of water for the Atlanta waterworks. The intake valve, where turbidity readings are taken, is just below the recording stream gage at Vinings, Ga. We can assume that the data collected at the intake valve and at the recording gage both reflect conditions of the entire watershed that serves Atlanta.

The Chattahoochee River above Vinings drains 928,000 acres, of which about 608,000 acres are in the foothills and some 320,000 acres are in the Piedmont Plateau physiographic area. The water at the intake valve is not polluted to any great extent by upstream sewage or industrial waste and is of excellent chemical quality for municipal or industrial use. But unfortunately the river is often muddied excessively by soil washed from watershed lands. A study of the pattern of land use in the drainage basin makes it possible to account for the probable sources of this difficulty.

Forests make up roughly 75 percent of the total area in the foothills part of the watershed. Some 46 percent of the land is in farms. The average farm has 76 acres, of which 62 percent is in woodland, 7 percent in open pasture, 18 percent in planted cropland, and 13 percent in idle or miscellaneous farmland. Approximately 73 percent of the planted cropland is used for clean-cultivated row crops. The average annual rainfall in the foothills area is 61 inches.

Throughout the hilly and rolling Piedmont Plateau area, forests now occupy about half the land area. Slightly more than two-thirds of the Piedmont area is in farms. The average farm has approximately 90 acres, of which 38 percent is farm woodland, 12 percent open pasture, 30 percent cropland, and 20 percent idle or miscellaneous farmland. Nearly three-fourths of the cropland is used for row crops. The average annual precipitation in the Piedmont Plateau area approximates 50 inches.

The flow and turbidity of the Chattahoochee River have been measured for more than 25 years at stations near Atlanta. The records show that the average annual turbidity has declined steadily from a high of 400 parts per million (p. p. m.) in 1934 to a low of 69 p. p. m. in 1952. Discharge, expressed as runoff in inches, did not indicate any trend, but seemed to follow the normal cycle of drought and excessive rainfall with heavy runoff.

River water would normally be expected to be most turbid when storms are most numerous. That is generally true if turbidity records are compared for the same month or season for areas that have not been greatly altered by special conservation practices.

Records for the Vinings gage show that the months of December through May generally have the greatest number of days during which discharge exceeds that considered critical for the study. Heaviest turbidity regularly occurs in June, July, and August, however, even though average runoff during those months is light in comparison with other months.

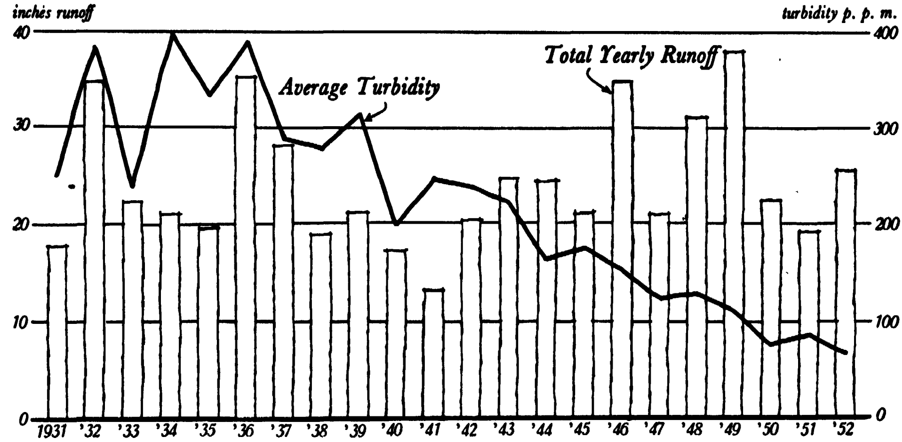
Summer storms are likely to bring heavy rainfall, small in amount but high in intensity and localized in extent. The runoff from such sudden downpours generally is excessive. Frequently the water flowing over the land causes great erosion, particularly on land recently tilled.

The pattern of turbidity and discharge of the Chattahoochee River in summer parallels the pattern that is based on yearly records. A substantial reduction in average turbidity in summer was brought about by improving the way land was managed. No abnormal fluctuation in the storm cycle was apparent. The month of August typifies the period.

Soil loss during the fall and winter for the 25-year period usually was moderate. Abnormally high monthly turbidity records usually could be

Average Turbidity and Annual Runoff, 1931–1952

Chattahoochee River Watershed, Atlanta, Ga.



traced to certain unusual disturbances, such as bridge construction and channel work. In winter the ground is often frozen and very resistant to soil displacement. Too, rains in winter usually are gentler than summer rains and are therefore less apt to wash soil out of place. Although improved conservation practices will have less chance to effect appreciable turbidity reduction during the nonactive crop season, one can ascertain a definite lessening of turbidity by scanning the monthly records. The data in the graph for May are typical.

Now let us see what the conservation programs have accomplished since 1930 to bring about the marked improvement in the quality of the water of the Chattahoochee River.

Acreage of the Chattahoochee National Forest in the watershed was increased. Nearly 40,000 acres of badly cutover and depleted lands have been acquired by the Federal Government since 1930. The lands have good protection against forest fires and are integral parts of sustained-yield management units. Some 40,000 acres were acquired between 1925 and 1930 and are showing the continuing effect of proper management and protection.

Protection against fires on private forest land was improved. In 1930 there was no organized forest fire protection of any kind for the non-Federal forest lands in the watershed. In 1955 the State fire organization protected more than three-fourths of these lands in the drainage basin.

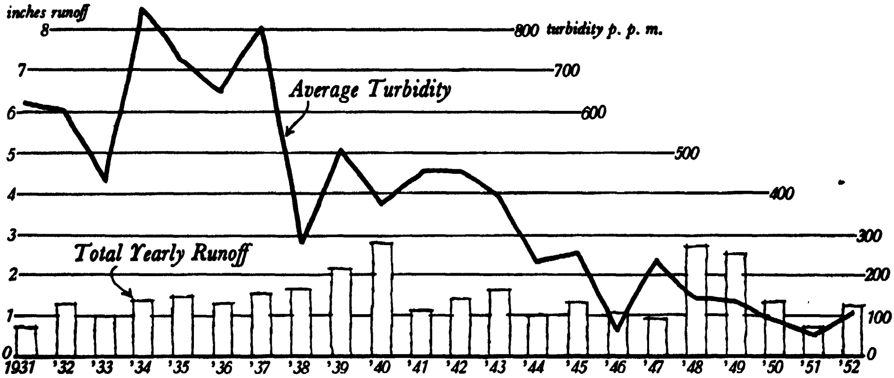
Stabilization of areas that are critical sources of silt is standard practice on road jobs of the Forest Service. Logging roads and skid trails in places where timber is sold are also receiving more adequate attention to insure less soil movement. State and county road officials are intensifying their programs for roadbank stabilization in the watershed.

More than 50,000 acres of wornout farmland has been planted to trees.

Soil conservation districts were organized in 1935. An estimated 60,000 acres of permanent, improved pasture have since been established; 4,000 miles of terraces have been constructed; and 52,000 acres are planted annually to cover crops. Good rotation practices are also in effect on about 60,000 acres. Other conservation practices, such as contour farming, construction of ponds, planting of kudzu, sericea, and perennial grasses, and stabilization of streambanks are being carried out to a lesser extent.

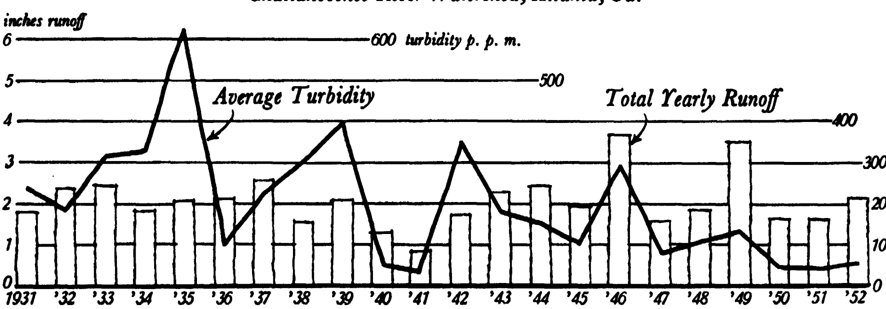
Average Turbidity and Total Runoff, August 1931–1952

Chattahoochee River Watershed, Atlanta, Ga.



Average Turbidity and Total Runoff, May 1931–1952

Chattahoochee River Watershed, Atlanta, Ga.



The acreage of harvested cropland declined by approximately 40 percent between 1930 and 1945. Most of the land retired from cultivation was on steep, eroding slopes, which normally are better suited for pasture or forest.

The conservation practices have reduced the turbidity problem in the Chattahoochee River watershed, but there is room still for improvement, especially during peak periods. Detailed studies may have to be made under a variety of conditions to show whether or not some of the practices need to be altered to meet local problems. However, we do have a set of basic recommendations on which sound watershed management plans can be established:

Encourage farsighted management for the more critical watershed lands. As these lands will often provide little or no income to the owners for a long time, returns may necessarily have to be deferred. Owners must know what is required to rehabilitate badly depleted lands of this kind.

Intensify efforts to improve logging and other practices on forest lands.

Provide State fire protection for all private forest lands in the watershed.

Extend management services to all owners of woodlands to achieve a double purpose: To develop higher forest values, which will be converted to profits by the owner and as such will be an incentive to carry out improved forestry practices; and to improve the forest floor and canopy covers, which will protect forest soils.

Table 1.—Average Annual Turbidity of River Water at 5 Georgia Waterworks Plants

Year of record	*Atlanta*[1] *(Chattahoochee River)*	*Columbus*[2] *(Chattahoochee River)*	*Macon*[2] *(Ocmulgee River)*	*State Hospital*[2] *at Milledgeville (Oconee River)*	*Augusta*[2] *(Savannah River)*
	p.p.m.	*p.p.m.*	*p.p.m.*	*p.p.m.*	*p.p.m.*
1931	258	......	......	......	......
1932	386	......	......	......	......
1933	240	......	......	......	......
1934	400	......	......	......	......
1935	335	......	216	......	......
1936	390	......	224	......	......
1937	290	......	161	......	......
1938	280	......	148	......	......
1939	315	......	163	417	......
1940	200	......	131	212	90
1941	250	......	133	125	59
1942	240	......	147	168	107
1943	225	......	110	142	104
1944	163	......	83	109	78
1945	178	85	105	121	95
1946	153	59	79	99	65
1947	124	42	79	108	67
1948	130	48	67	96	57
1949	111	31	58	78	43
1950	76	29	45	62	44
1951	88	35	45	86	58
1952	69	33	63	45	41
1953	76	36	51	44	26

[1] Source, Atlanta Waterworks.
[2] Source, Soil Conservation Service.

Table 2.—Storm Record for the Chattahoochee River Above Vinings, Ga. (Atlanta Watershed) as Indicated by Turbidity, Runoff, and Storm Discharge

[Records from January 1931 through September 1953]

Month	*Average turbidity (p.p.m.)*	*Average runoff (inches)*	*Number of days average stream discharge exceeded: 2,500 second-feet*	*Number of days average stream discharge exceeded: 10,000 second-feet*
January	153	2.94	14.5	1.6
February	172	2.81	16.6	1.4
March	183	3.25	21.7	1.7
April	196	2.86	20.2	.8
May	192	2.10	13.2	.0
June	336	.60	5.7	.1
July	453		5.4	.5
August	368		4.6	.3
September	199	.09	2.2	.2
October	112	.15	2.3	.3
November	87	..32	3.0	.4
December	120	2.24	7.9	1.2

Plant trees on lands not suited for cultivation or pasture. Such lands, usually depleted and lacking adequate cover, are primary sources of sediment. Trees will bring the land back into commercial production and will build up a forest floor, which will do much to stop the movement of soil.

Intensify farm programs to obtain the maximum participation in carrying out such practices as pasture improvement and seeding, contour farming, cover cropping, planting of permanent grasses, construction of farm ponds, terracing, and crop rotations.

Intensify roadside stabilization work on State and county roads and encourage loggers to adopt practices that will reduce the amount of soil washing into water channels. Such practices as seeding grass on abandoned logging roads, proper location of roads, and construction of enough water bars will help to reduce the turbidity of the streams.

Turbidity in a stream indicates that

rain, instead of entering the ground, is passing over the surface and taking soil with it. Never before has our interest been greater than now in obtaining high yields of usable water for domestic and industrial use. Downstream users must have the best water that a watershed can produce. Good watershed management is a way to get it.

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ALBERT H. SPECTOR *was graduated from the Pennsylvania State University in 1940. He joined the Forest Service in 1946 and was assigned to the Division of Flood Control Surveys in 1948. He has worked on flood surveys in the South since then as a land-use specialist and as a watershed planning specialist. He is attached to the Division of State and Private Forestry.*

The Story of Sandstone Creek Watershed

Harold M. Kautz

Because everybody helped, the Sandstone Creek watershed in western Oklahoma is not the problem it was.

The board of supervisors of the Upper Washita Soil Conservation District took an active part in the formation and affairs of the Washita Valley Flood Control Association. The Flood Control Act of 1944, which authorized works of improvement to retard runoff and prevent erosion on upstream watersheds of the Washita River watershed, gave them added incentive.

When the Congress appropriated funds for planning upstream flood prevention work in 1946, the district supervisors had selected the watershed on which they wanted assistance.

Sandstone Creek was the watershed they and farmers and ranchers selected. It lies within an area on whose boundaries are the towns of Sayre, Elk City, Hammon, and Cheyenne, Okla. The creek flows northeast for 15 miles and enters the Washita River about 8 miles southwest of Hammon.

The entire Sandstone Creek watershed lies in the Rolling Red Plains. The shallow nature and steep topography of 85 percent of the upland soils makes them suitable only for range purposes. The remaining 15 percent of the upland is cultivated, principally in small farm units. The economy of the watershed is agricultural. Livestock provides the major source of income to the landowners.

Ownership of the 4,700 acres of bottom land in the watershed is closely associated with ownership of the ranch lands that surround the valley. Consequently slightly more than 90 percent of the cultivated bottom land is used for crops that support livestock production—small grains, grain sorghums, and alfalfa.

Sandstone Creek lies in the 25-inch rainfall belt, and has periods of drought as well as intense rainstorms. During droughts the watershed cover tends to become depleted unless the range is carefully managed. Poor cover conditions cause greater runoff from the watershed and increased flooding of the bottom lands. Loss of supplemental feed crops due to flooding often leads to heavier grazing of the uplands, and the circle of events is repeated. Such were the conditions when the Soil Conservation Service was asked to help the local people solve their problem.

FLOOD PROBLEMS and damages were studied as a basis for determining the type of structures and practices needed

to insure normally safe farming and ranching operations.

The 20-year period 1920 through 1939 was selected as representative of normal rainfall in the area. During that period 184 storms caused floods; 59 of them caused damage. In some instances the storms occurred so closely together that damage from the previous storm had not been repaired or recovered. Sometimes several storms occurred during harvest, and only the largest one in that season was evaluated. In the 20 years numerous floods and the great drought of the early 1930's occurred.

Sediment damage was severe. Improper land use and management had increased surface runoff, so that the main channels had been deepened at the headwaters and numerous gullies had developed. Most of the gullies were 6 to 20 feet deep and 10 to 50 feet wide at the top. The soil on the sides of the gullies generally was not sufficient to support vegetation dense enough to control erosion on the banks.

Overbank deposits of sediment were present on 4,115 acres of the 4,700-acre flood plain. Approximately 3,700 acres were covered to depths of 1 to 8 feet. As the loss of topsoil by erosion increased, the deposited material became more sandy and less fertile. Costs of crop production went up as a result, and productivity of the valley land went down.

Not all the sediment was deposited on the valley lands. Some was dropped in the stream channels. That occurred mainly in Currant Creek, a major western tributary of Sandstone Creek, and in the lower reach of the main stem. Two-thirds of the total length of the Currant Creek channel was filled with sand. The lower Sandstone Creek channel was filling at the rate of 4 to 8 inches annually. The reduced channel capacities caused more frequent flooding and increased deposition of sediment on the bottom lands.

Information was obtained from more than three-fourths of the landowners or operators in the flood-plain area to determine the extent of flood damage to crops, land, and other agricultural property caused by floods within their memory. They provided information also on land use, acreages of various cultivated crops, and the value of the flood-plain land. Damages to roads and to bridges were reported by the county commissioners.

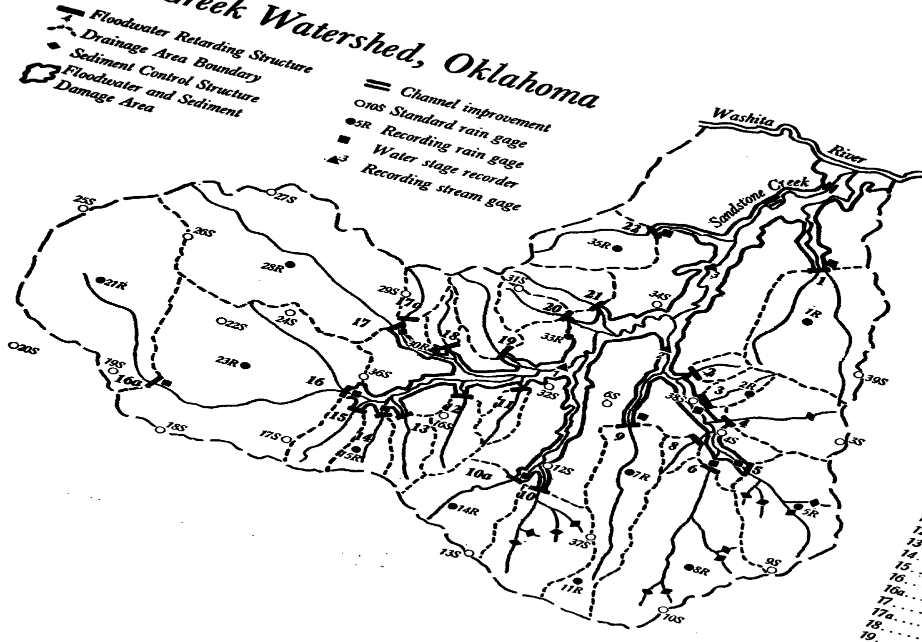
All this basic information was used to determine the damage from floods and sediment. The average annual damages in dollars were: Crop and pasture damage, 40,100; flood-plain scour, 400; streambank cutting, 2,200; other agricultural damages such as loss of livestock, fences, and equipment, 3,900; road and bridge damage, 1,000; deposition of sediment on valley lands, 5,700; indirect damages, 5,300.

A WATERSHED PLAN designed to reduce erosion and flood-water damages was developed by the soil conservation district supervisors, landowners, interested organizations, and agencies of Government. The plan called for the conservation treatment of the farmland as a means of protecting it against excessive soil loss and runoff. The plan also called for such measures as detention dams to retard floodwater, sediment-control dams, and channel improvement.

The total needs of the watershed included more than 400 miles of terraces and 50 acres of vegetated farm waterways, to help control erosion on 6,200 acres of cultivated land; seeding 5,800 acres of idle or severely eroded cropland to native grasses; 125 farm ponds, to promote proper distribution of grazing on rangeland and pastureland; improved crop rotations on 6,200 acres of cropland; and improved range and pasture management on 58,800 acres. Supplemental measures included 24 floodwater-retarding structures, 13 sediment-control dams, and a mile of channel improvement.

The size of the watershed in relation to the carrying capacity of its channel is such that only one-quarter inch of runoff from the watershed can cause a

Sandstone Creek Watershed, Oklahoma



Site No.	Drainage Area
1	3,411
2	334
3	399
4	1,775
5	2,492
6	4,133
8	292
9	2,243
10	2,261
10a	1,837
11	449
12	862
13	691
14	652
15	758
16	7,338
16a	5,618
17	6,483
17a	534
18	390
19	990
20	589
21	922
22	1,442

flood. Complete installation of the soil conservation measures therefore would not prevent overflows.

The 24 floodwater-retarding structures were planned to control the runoff from 70 percent of the total watershed and protect 95 percent of the flood plain. Water held back by the structures, located near the extreme head of the flood-plain areas, would permanently inundate only 139 acres of bottom land. An additional 63 acres of bottom land would be covered temporarily by the stored floodwaters.

A typical floodwater-retarding structure in this locality has an average drainage area of 5 or 6 square miles. The floodwater-detention pool is designed to hold back at least the maximum runoff to be expected once in 25 years. Floodwaters temporarily stored behind the dam are released slowly through an ungated drawdown tube. As a result, the water is carried by the channel without overflowing the bottom lands below. The lower part of the storage basin is reserved for the deposition of sediment. The storage allotted for this purpose is enough to insure that the structure will operate at full efficiency for at least 50 years. The dam is equipped with a vegetated spillway capable of handling the runoff from a storm of 100-year frequency occurring when the detention basin is full. Such a design produces an economical structure that is capable of withstanding extremely large storms. Its economy lies in the simplicity and range of design. No attempt is made to store the runoff from major storms because approximately 95 percent of the total flood damages in a watershed of this type are caused by the smaller storms that occur more frequently than once in 25 years.

Thirteen grade-stabilization or sediment-control dams of the drop-inlet type were planned in the larger, more active gullies that could not be healed by vegetation alone. The justification for these structures was based on the overall sediment storage required both in the sediment control dams and the detention dams to reduce sediment damage on flood-plain lands.

One mile of channel improvement also was proposed in the lower end of the main stem to counteract flooding conditions brought about by sediment deposition in the channel.

An evaluation of the effect of the program disclosed that the 25-year-frequency storm would flood 3,600 acres of bottom land under existing conditions. If such a rain were to occur after the needed conservation measures and proposed dams had been installed, only 340 acres would be flooded. With the program in place, only 2,190 acres would be flooded by all the storms such as occured during the 20-year rainfall period investigated, or an average inundation of slightly fewer than 110 acres annually. The estimated remaining average annual floodwater and sediment damage of 1,240 dollars represents an average reduction of 57,360 dollars annually.

Benefits do not end with reduction in flood damage. The owners indicated that if flood protection were provided they would make more intensive use of the flood plains. Lands producing low returns from small grains or pasture would be used to grow higher value crops, such as alfalfa. The annual net benefit from this more intensive land use was estimated to be 11,000 dollars.

The biggest benefit of all will be derived by landowners in the upland area through the protection and proper use and management of their soils. It was estimated that their combined net income would be increased about 88,000 dollars annually by the application of good conservation measures.

Total benefits from the recommended program on Sandstone Creek were calculated to be approximately 3 dollars for each dollar of cost.

Farmers and ranchers cooperated wholeheartedly in the program. By the time the watershed plan was completed and approved by the local people, soil and water conservation plans had been

prepared on 87 percent of the watershed through cooperative agreements between the landowners and the soil conservation districts.

Late in 1948, with 60 percent of the needed land treatment practices and measures applied on the land, the supervisors of the soil conservation district and others set about the task of obtaining easements for the proposed structures. All easements except one were granted without charge to the Upper Washita and North Fork of Red River Soil Conservation Districts. The cost of the one easement and the cost of relocating one well were borne by the Upper Washita District. An agreement was also reached with the County Commissioners' Court of Beckham County whereby it would construct one of the sediment control dams, which was located on a county road. The value of easements, removal of obstacles, and assistance in construction furnished by local interests was estimated at 60,000 dollars.

The obligation of maintaining the water management structures was assumed by the soil conservation districts. They, in turn, sponsored the organization of the Sandstone Creek Watershed Maintenance Association. Again outstanding interest was shown when many of the upland owners, as well as the benefited flood-plain landowners, joined the association.

SANDSTONE CREEK thus became one of the first watersheds in the Nation ready for the installation of a complete flood-prevention program.

A cooperative evaluation program was developed by the Soil Conservation Service and the Geological Survey to determine the effects of land treatment and structures on rainfall-runoff relationships, ground-water recharge, streamflow, and sediment production to get information that would be of importance to all groups interested in the conservation, use, and management of water.

Fourteen recording and 25 standard rain gages were installed over the 100-square-mile watershed. Water-stage recorders were located on 11 of the 24 floodwater-retarding structures. Sedimentation ranges were established for future use in measuring sediment deposition in the pool areas. The 11 structures were selected to provide a range in shape and size of drainage area, land-use pattern, soil types, and cover conditions. Arrangements were made to inventory the condition of the drainage areas annually in order to provide a basis for evaluating the effect of land use and management on sediment production and runoff into the structures.

Three automatic stream-gaging stations were located on the major tributaries and main stem of Sandstone Creek to measure monthly and annual streamflow, peak discharges from storms, and return flow to the stream by water that had been infiltrated into the soil. In addition, four wells were selected for observing changes in ground-water level.

THE FIRST CONSTRUCTION CONTRACT was awarded in June 1950. It covered structures at sites 5 and 9. A policy of awarding contracts on small groups of structures was followed throughout the construction period to encourage small contractors to bid. The grouping of structures also made it possible for a few men to supervise construction.

Construction of the dams was completed in November of 1952. This left to be done only the mile of channel improvement proposed on the lower main stem, where sediment deposition had been gradually reducing the channel capacity. Because structures and conservation measures on the watershed would produce prolonged flows and reduce the sediment load in the stream, however, it was decided to delay the channel improvement for a few years to give nature a chance to rectify conditions at no additional cost.

EVALUATION of the watershed program has been hampered by a drought that began with the installation of the structures and gaging stations. The

rainfall in 1952 was only 13.32 inches. The rainfall in 1953 was 20.10 inches, but much of it fell as ineffective, light showers. Storms of 2-inch proportions occurred on only three occasions during the year. There were 322 days of no rain.

The first storms of any importance occurred on April 25, 27, and 29, in 1954. The first was relatively light and occurred between 10:00 and 11:00 p. m.; precipitation ranged from 0.55 to 1.11 inches over the watershed. The highest intensity was at the rate of 3.60 inches an hour. Early in the evening of April 27 a short, intense storm was recorded. The rainfall ranged from 0.10 to 2.11 inches; most of it fell in 20 minutes.

The largest and most intense of the storms took place between 10 p. m. and midnight on April 29. Only a trace of rain fell in the southeastern part of the watershed, but gage 35R in the northwestern part recorded 3.71 inches. The highest intensity for a 5-minute period, equivalent to 6.6 inches an hour, was recorded at gage 30R. The heaviest part of the storm therefore fell across the drainage areas of floodwater-retarding structures 18 to 22 and in the lower part of the watershed, where structures had not been built because sites were not available.

THE MAXIMUM intensity for 1 hour was recorded near structure 18 as 3.2 inches an hour. Rainfall over the drainage area of structure 22 was 3.69 inches in 2 hours. Such rainfall intensities are to be expected there once in 50 and 25 years, respectively. The amount of the precipitation has been exceeded in this watershed several times. But the intensity of the rainfall, the ineffective condition of the vegetative cover because of the prolonged drought, and the rainfall of April 25 and 27 combined to produce excessive runoff from the storm of April 29. The weighted runoff for the watershed amounted to 1.39 inches, or 63 percent of the rainfall.

The floodwater-retarding structures handled the runoff without difficulty. The highest stage reached in any structure was at site 1, where the maximum water level was 11.8 feet below the spillway crest. The effectiveness of the floodwater-retarding structures in reducing flood flows was shown by the fact that the structures above stream gage 1 released only 200 acre-feet of flow during the period of surface runoff from the 38.7 square miles of drainage area controlled. In contrast, the 6.3 square miles of uncontrolled drainage area above stream gage 1 produced 720 acre-feet of runoff during the same period.

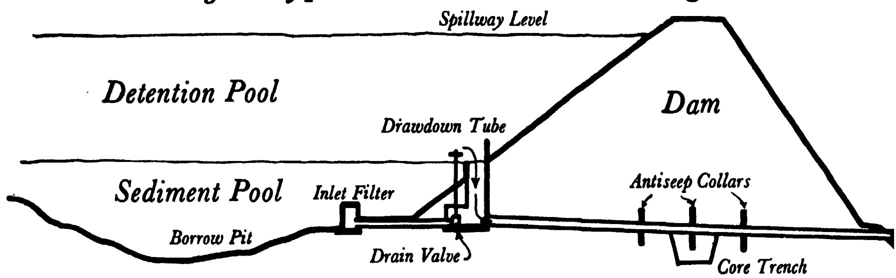
The coordinated land treatment and structural measures prevented any flooding during the storms of April 25 and 27. Runoff from the April 27 storm, however, caused the collapse of a condemned bridge across the main stem of Sandstone Creek in the central part of the watershed. The destruction of the bridge was due to bank cutting with the flow at less than channel capacity.

The April 29 storm inundated 588 acres of flood plain. Most of the flooding occurred in the lower reach of the main stem, where channel improvement had been planned but not yet constructed. Sediment was deposited on 330 acres of bottom land, and an additional 24 acres suffered moderate scour damage. Sedimentation damage was light, since the deposition generally was less than 6 inches in depth.

If such storms had occurred before installation of the land-treatment measures and floodwater-retarding structures, approximately 2,160 acres of the 4,700-acre flood plain would have been inundated, sediment damage could have been expected on 1,880 acres, and about 130 acres of bottom land would have been damaged by scour channels.

Upland damage generally was slight to moderate. Damage was severe only on small areas. Sediment damage to terrace channels was slight. Erosion was minor in places where the land was in small grain or other protective

Section of a Typical Floodwater-Retarding Structure



crops. Some of the cultivated land had been prepared for cotton or sorghums, but not planted. In some instances the terrace channels on this land were blocked with sediment, and erosion occurred where the terraces were overtopped.

Most of the range and retired cropland consists of shallow to very shallow soils on rolling to steep slopes. Runoff was relatively high, but erosion losses were slight. As nearly all the stock ponds have been built on this type of land, sediment damage to ponds was not excessive. Only 2 of the 120 ponds were damaged.

The total upland storm damage to this 100-square-mile watershed was estimated to be 6,150 dollars, the major part being due to the need for extra maintenance and repair of terraces that are not designed to withstand storms of this size.

The watershed protection and flood prevention measures reduced floodplain damages from the April storms from 25,850 dollars to 5,770 dollars. This meant a reduction of 78 percent in damages and a saving to the landowners of slightly more than 20,000 dollars. More than half of the saving was brought about by the prevention of damage to crops and pasture.

A MORE VIOLENT STORM came less than a month later. Rain started falling about 6:00 p. m. on May 23, and by midnight rain gage 23R had recorded 6.0 inches of precipitation. An additional 1.17 inches fell slowly on May 24, with a period of no rain between 4:00 a. m. and 10:00 a. m. The storm centered above structures 16 and 17 in the western part of the watershed, where the maximum of 7.17 inches was measured. Rainfall along the eastern edge of the watershed ranged from 4.0 to 4.6 inches. Precipitation was relatively heavy over the entire drainage area.

Rain gage 23R recorded 0.58 inch in one 5-minute period, a rate equal to about 7 inches an hour. It also gaged 5.10 inches in 2 hours. (The maximum expected rainfall for a 2-hour period once in 100 years is about 4.9 inches.) The average rainfall over the watershed was 4.37 inches. Only 1.35 inches, or 31 percent, appeared as runoff. The runoff from the storm was slightly lower than that of April 29, because the heaviest part of the May storm fell in an area of sandy, permeable soils.

While the storm of May 23–24 was considerably greater in total amount and intensity than the April 29 storm, flood damage was less extensive—mainly because runoff from the heaviest part of the May storm was controlled by floodwater-retarding structures 16, 16A, and 17. The highest stage reached in any of the structures occurred at structure 16, where the maximum water level in the detention pool was 7 feet below spillway crest.

Runoff from the May storm caused flooding on only 200 acres of bottom land, all of it in the lower reach of the main stem planned for channel improvement. Otherwise the stream remained well within banks.

The areas that were damaged by

sediment and scour had been damaged by the previous storm, and the additional damage was minor. Sediment was deposited in a relatively thin layer on 45 acres. No new scour channels were created, but scour channels caused by the April storm were deepened 3 to 6 inches on about 18 acres.

Besides the upland damage caused by the earlier storm, 50 miles of terraces were damaged to the extent that light maintenance was required and 100 miles needed more extensive repair of breaks. An estimated 250 acres of cropland that had not been planted to a protective cover had fairly severe erosion and scour damage. Sediment damage to stock ponds was estimated to equal 50 percent of the expected annual sediment damage. Total upland damages were estimated to be 2,300 dollars. This figure is smaller than that for the April 29 storm because the terrace breaks and other damages it had caused had not been repaired by the time the storm of May 23–24 occurred.

DAMAGES ON THE flood plains would have been high had the protective measures not been installed in the watershed. Flood routings made of the storm runoff, assuming before-treatment conditions, indicated that 2,110 acres would have been flooded, some degree of sediment damage would have occurred on 1,880 acres, and about 210 acres would have been damaged by scour channels.

Monetary floodwater and sediment damages would have amounted to 22,275 dollars—a figure that takes into account damages that would have occurred as a result of the April storm and would not have been repaired or recovered at the beginning of the May storm. Actual damages amounted to only 1,100 dollars. The saving to the people was 21,175 dollars.

THE GOALS SET by the residents, as indicated by their acceptance and approval of the watershed work plan, were to install all needed conservation measures on the watershed lands and maintain the measures; prevent 90 percent of the flood damages, such as had been occurring on the bottom lands along the creek; and intensify the use of the protected flood-plain lands in order to permit proper use and management of the uplands.

At the time of the April and May storms, the farmers and ranchers had completed 85 percent of the conservation job on the watershed. While the extended dry period caused some of the conservation measures to function at considerably less than 100 percent efficiency, their effectiveness in protecting the land during the heavy storms amply demonstrated the importance of land-treatment measures in protecting the landowner's investment and income. It is expected therefore that the rate of application of conservation measures will increase, with the return of more nearly normal rainfall conditions, until the whole job is done.

THE COORDINATED conservation and structural measures saved 41,255 dollars of the 48,125 dollars in flood damages that would have occurred as a result of the April and May storms had the measures not been installed—a reduction of 86 percent. Considering the fact that the program will provide 100 percent protection to the flood plain from most of the smaller storms, the goal of 90 percent protection is sure to be attained.

During the time that the work plan was being developed, the flood-plain landowners stated that if flood protection were provided they would intensify their use of the flood-plain lands within 5 years by growing a larger proportion of high-value crops that would increase their net income and produce more livestock feed, a practice that would permit them to use their uplands properly. They would, for example, reduce their acreage in small grains from 1,830 to 1,360 acres; increase the alfalfa acreage from 570 to 1,270; increase the cotton acreage from 225 to 270; and reduce the acreage in

pasture from 1,380 to 1,270 acres. By June 1954, less than 2 years after the structures were installed, more than one-half of the indicated changes had been made.

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Quantities of Water Available for Use in Major Drainage Areas; October 25, 1954

[*Total surface and ground*]

Major drainage areas		*Average annual runoff*			
Name	*Thousands of square miles*	*Inches*	*MAF*	*BGD*	*Thousands of cfs*
New England	73	23	90	80	124
Middle Atlantic	102	17	92	83	128
Gulf and South Atlantic	251	16	214	191	296
Great Lakes–St. Lawrence [1]	128	13	89	79	123
Ohio River	163	16	139	124	192
Tennessee Valley	41	22	48	43	66
Lower Mississippi	64	16	55	49	75
Souris and Red [1]	60	1.6	5.1	4.6	7.1
Upper Mississippi Basin	188	7.6	76	68	105
Missouri Basin [1]	520	1.9	53	47	73
Arkansas-White-Red	264	6.9	97	87	134
Rio Grande and Gulf	341	3.2	58	52	80
Columbia Basin [1]	219	8.4	98	88	136
Great Basin	186	1.1	11	9.7	15
Colorado Basin	272	1.1	16	14	22
North Pacific	38	45	91	81	126
Central and South Pacific	48	13	33	30	46
Central Valley	64	10	34	30	47
United States	3,022	8.1	1,299	1,160	1,795

[1] Includes only that part of basin in the United States.

"Inches" is equivalent depth on the drainage area.

"MAF" is millions of acre-feet and equals inches times drainage area divided by 18,750.

"BGD" is billions of gallons per day and equals inches times drainage area divided by 21,002.

"Thousands of cfs" is thousands of cubic feet per second and equals inches times drainage area divided by 13,574.

NOTE.—Table shows average annual runoff originating in each basin as estimated on basis of stream-flow records for the period 1921–45 and compiled in part from maps and data in U. S. Geological Survey Circular Nos. 44 and 52. Average annual runoff represents the total amount of water (surface and ground) available for use on a continuing basis. Because of yearly fluctuation in the amount of runoff, the amount of water available in any one year may vary widely from the above average. The table does not include water available from ground water storage not perennially recharged. For surface and ground water supplies at specific locations, see Water Supply Papers of the U. S. Geological Survey.

Water and Our Forests

Trees Also Need Water at the Right Time and Place

G. L. Hayes and Jesse H. Buell

Water is essential to all plantlife, but trees, the giants of the plant world, require exceptional amounts.

Nearly three-fourths of the weight of a living tree is either water or is made from water, and one old-growth redwood tree may weigh as much as 300 tons. The amount of water that is retained by trees, however, is insignificant compared to the amount that is evaporated—transpired—from the leaves. As much as 1,000 pounds of water may be transpired for every pound of dry wood produced.

Organic life very likely originated in the waters of prehistoric seas. Many forms of plants and animals have long since migrated to the land, but their physiology is still inextricably connected with water. Trees are not exceptions, and the water available for tree growth determines in large measure where trees can grow, what kinds can grow, and how big they can grow.

Just as with all other green plants, the growth of trees starts with the intake of the materials that are combined chemically to make the wood, bark, leaves, and fruits of the trees. Water is one of the essential growth materials. The others are carbon dioxide, nitrates, and several kinds of minerals. Water, nitrates, and minerals are absorbed from the soil. The nitrates and minerals are absorbed in water solution. They cannot enter trees in any other form. Even the carbon dioxide, which the trees extract from the atmosphere, passes into water solution as soon as it enters the cells of the leaves. Once inside the trees, all movement of materials takes place in water solution and all chemical reactions take place in water.

Many chemical changes take place in the watery solutions of trees as the water, carbon dioxide, and other materials are combined as chemical building blocks to make up the physical structure of the trees.

The first of the changes, the process called photosynthesis, is of special significance to us all. By photosynthesis, trees trap and store large amounts of energy from the sun in the form of glucose, a simple carbohydrate: Water plus carbon dioxide plus energy yield glucose plus oxygen.

The glucose is an intermediate step in making more complex carbohydrates, rich in solar energy, which ultimately make up by far the bulk of the bodies of trees. Trees of the prehistoric past fell into swamps, carrying with them their rich store of solar energy, and formed coal and crude oil. When we burn wood, coal, or oil to heat our homes or use gasoline to propel our vehicles, we are utilizing energy stored by photosynthesis. But photo-

synthesis is not peculiar to trees alone; it is carried on by all green plants. And plant carbohydrates ultimately are the sole source of energy foods for all animals, including man. About six-tenths of the weight of plant carbohydrates is oxygen derived from water.

Water has yet another function in trees—the maintenance of turgor, the pressure in the living cells that keeps the plants firm. That function influences the rate of growth and ultimate height of the trees. It can be changed by forest cultural practices. Growth of trees is the end product of a series of chemical and physical processes that take place in the living cells. The processes can proceed at full speed only when the contents of the cells are diluted with water and the cells are tightly expanded by internal water pressure. Whenever the water content of the cells declines, vital changes take place. The cell contents become more concentrated. That slows up all the physical and chemical processes in the cells and therefore curtails growth. If the cell water drops too much, irreversible changes take place in the living contents of the cells, and all affected parts die.

To be able constantly to keep the cells full of water is so important that all trees have a built-in mechanism for regulating loss of water. Water is lost mainly by transpiration—evaporation through minute openings in the leaves, called stomata or stomates. When the water pressure in the leaf cells drops, the stomata close to restrict further loss. But the leaf stomata are also the passageways through which carbon dioxide enters the trees, and they are normally open whenever there is light enough for photosynthesis. When they close to restrict water loss, they cut off the supply of carbon dioxide that is essential for photosynthesis. Therein lies a basic conflict in the lives of trees. Carbon dioxide can be assimilated only through open stomata. But when the stomata are open, transpiration takes place unhindered. Excessive transpiration reduces water pressure in the cells and thereby curtails growth. To protect against excessive water loss and death of affected parts, the stomata close, restricting intake of carbon dioxide and further restricting growth. In those ways, water has a leading role in regulating the rate of tree growth.

The condition of the atmosphere affects the rate of transpiration. It is greater when the air is hot, dry, or windy. It is less when the air is cool, moist, or calm. As wind speeds are commonly low near the ground and increase rapidly with distance above ground, trees are subjected to ever-increasing transpiration as they grow taller.

The ability of a tree to replace transpired water is limited by the soil water available and its water transportation system. As the trees grow taller, the prompt replacement of transpired water becomes more difficult. Larger trees have more foliage to transpire water, they grow more wood annually, and their crowns project higher into the winds. Furthermore, they have to lift the water higher and that requires more energy, some of which may have to be obtained by the destruction of carbohydrates which might otherwise be used for growth. On hot, dry, windy days, transpiration readily exceeds the ability of trees to replace losses immediately. Internal deficits of water follow. As the trees grow taller, water deficits become more chronic and acute; growth, especially of the highest points, becomes slower and slower, and the trees lose vigor. It is easy to see that a lack of water can restrict the height of trees.

Trees never grow very tall in climates where the air is dry and strong winds blow during the growing season. Even if they grow on stream banks with their roots in an inexhaustible supply of water, transpiration may be faster than the rate at which the tree can move more water from the roots to the leaves. On the other hand, trees grow tallest in environments where rates of transpiration are low. Under those conditions, normal cell turgor can be

maintained more of the time; growth can be more rapid and can be continued until the trees are taller. Trees grow larger in sheltered mountain coves and the interior of isolated groves than they do on windswept ridges and the exposed borders of groves. The redwoods, the tallest trees on the North American Continent, grow in the Pacific coast fog belt, where the atmosphere is humid. Douglas-fir grows fastest and tallest in the more humid parts of its range.

Trees may grow taller within the shelter of a dense forest than they could have if more exposed to winds. When dense forests are thinned out by fire, insect attacks, or partial cutting, the remaining trees are exposed to excessive transpiration. It is not uncommon for these suddenly exposed trees to decline rapidly in vigor, and often the tops are killed back for several feet.

THE LARGE WATER REQUIREMENTS of trees limit them to the wetter parts of the world. The distribution of forests and of tree species throughout the world is controlled primarily by climate in terms of heat and water. Wherever it is warm enough for trees to grow, water determines their distribution and kind. Different kinds of trees have different requirements for moisture.

Trees, like other plants, have been changing through the ages. Organic evolution has produced thousands of different kinds. To even the casual observer they differ strikingly in appearance: Some have needlelike leaves, others have broad leaves; some shed their leaves annually, others retain them throughout the year; some bear acorns, others cones. They also differ strikingly in their habitat requirements. Some require abundant soil moisture, others can live on little; some require abundant moisture throughout the year, others for only part of the year; some require a humid atmosphere, others tolerate one that is dry. Through centuries of evolution, plants have been developed that are adapted to almost all conditions of moisture that are found on the earth. Many hundred species of trees have evolved which are adapted to a wide variety of the wetter habitats.

Forests generally are the dominant vegetation wherever annual precipitation exceeds about 25 inches. Lands too dry for forests commonly support grasses or drought-resisting shrubs. The relation of forests to precipitation is not a simple one, however. The amount of water that is available for tree growth cannot be expressed in terms of annual precipitation alone. Less water is required where evaporation and transpiration rates are low than where they are high. Less rain is therefore required in cool regions than in hot. Parts of the Tropics that have as much as 40 inches of rain are treeless. Twenty inches or more annually is needed by ponderosa pine in New Mexico, but 15 inches is sufficient in Montana. The spruce and fir forests of Saskatchewan receive no more precipitation than the grass-covered plains of North Dakota.

Less precipitation is required for the forests where the atmosphere is moist than where it is dry. And less rain is required on porous, sandy soils than on heavier soils that water penetrates slowly. Moisture-loving redwoods grow with as little as 25 inches of rain in the Pacific coast fog belt, where transpiration losses are small. The extensive heavy soils of the Russian steppes, the short-grass plains, support only short grasses, but low hills of sand that are found in parts of the steppes are tree-covered.

Forests also require a dependable water supply. In moving westward, early settlers found the great forests of the Eastern States giving way to grass-covered prairies in Illinois and adjacent States, although there was no material decline in average annual precipitation. The ending of the forest coincided with a change in dependability of moisture.

Edgar N. Transeau, in an article in *Ecology* in 1935—volume 16, pages

423–437—showed that over the prairies, precipitation varies more from year to year, droughts are more frequent and severe, precipitation is not so evenly distributed throughout the year, and the atmosphere is drier in summer. The extreme droughts of 1913–1914 and 1930–1934 killed many trees on the prairie margin, and the forest boundary was pushed back. The occasional severe droughts apparently stop the forests from migrating westward.

Winter precipitation is more effective than summer precipitation for trees. Evaporation and transpiration rates are low in winter. Successive rains can accumulate in the soil and penetrate deeply, or snow can pile up on the ground and saturate the ground when it melts. On the other hand, summer rains fall when warm winds and actively growing plants return water rapidly to the atmosphere. There is seldom a surplus of moisture to penetrate to the deeper layers of soil. Thirty inches of rain, falling mostly in winter, is enough for Douglas-fir forests in southwestern Oregon. But the same amount falling mostly in the summer produces only grasses in Iowa.

Even the form in which precipitation falls may affect the distribution of forests. The lower level of the forests on the west slope of the Sierra Nevadas in California approximates the level of persistent winter snow. And Mr. Transeau showed that the boundary between the northern conifer forest and the northern hardwood forest of the eastern United States approximates a line which receives 40 inches of snowfall annually.

THE DISTRIBUTION of the world's forests in relation to water is made especially clear by classifications of world climates. C. W. Thornthwaite's classification in *Climate and Man*, the Yearbook of Agriculture, 1941, includes a division of the earth into warm and cold zones. In the warm zone, "effective precipitation" largely determines what kinds of vegetation will grow. Effective precipitation is the amount available for plant growth, or total precipitation minus runoff and evaporation. The warm zone extends from the Equator to about 50 or 55 degrees of latitude (approximately the northern border of the United States). In the two cold zones which lie poleward from the warm zone, plants are not able to utilize fully the amount of water usually available in the short growing season. Temperature efficiency is therefore more critical in determining kinds of vegetation.

Dr. Thornthwaite divided the warm zone into five moisture provinces and the cold zone into three temperature provinces for a total of eight major climatic provinces in the world. Each province has a typical vegetation type. Forests are the typical vegetation in the two wettest of the moisture provinces and in the warmest of the temperature provinces.

Moisture province	*Vegetation*
A—superhumid	rain forest
B—humid	forest
C—subhumid	grass
D—semiarid	steppe
E—arid	desert

Temperature province	*Vegetation*
D′—taiga	coniferous forest
E′—tundra	mosses, lichens, sedges
F′—permanent frost	none (ice and snow)

The influence of water on forest distribution is especially clear-cut in tropical regions, where heat is sufficient for tree growth everywhere. The Tropics extend on either side of the Equator for 23.5 degrees of latitude. On the North American Continent, the tropical zone extends to northern Mexico and does not quite reach the southern tip of Florida.

The climates of the Tropics form a regular pattern, which includes all five of Dr. Thornthwaite's moisture provinces. From superhumid and humid in the equatorial belt, where it rains almost daily, they grade away both north and south through subhumid and semiarid provinces, which are wet for part of the year and dry for part, into an intermittent belt of deserts

around the world, which marks the north and south limits of the Tropics.

Vegetation shows a similar gradation. The dense rain forests of broad-leaved evergreen trees do typify the superhumid province of the equatorial belt. To the north and south, the nature of the forest changes in adaptation to the diminishing moisture. The forests become shorter and less dense. The trees are broad-leaved, deciduous kinds that shed their leaves and turn dormant during the dry season. They would not be able to survive the hot, dry season if they retained their leaves, and continued to transpire when soil water was not available. Beyond the limits of the humid province, the forests give way to scattered, often thorny scrub trees in grasslands (savannas), which in turn change to steppes and deserts in the semiarid and arid provinces.

The Temperate Zones, which lie between the Tropics and the Arctic and the Antarctic Circles, have more complex climates than the Tropics.

They include all five of the moisture provinces plus the warmest of the temperature provinces, the taiga.

Temperate Zone climates can best be illustrated by a reference to the North American Continent. An important climatic boundary line extends from the central part of Maine northwestwardly to southern Alaska. The moisture provinces lie south of this line, and the temperature provinces lie north.

The part of the continent that is included in the moisture provinces can be divided into three roughly equal parts. The eastern one-third is humid, with precipitation evenly distributed throughout the year. The central one-third is subhumid to arid, with more precipitation in summer than in winter. The western one-third is a mountainous land, where the moisture supply differs greatly from place to place.

Between the Rocky Mountains and the mountain barrier formed by the Sierra Nevada and Cascade Ranges of the west coast, the mountains govern the moisture supply. The moisture provinces are arranged in altitudinal bands on the mountains, increasing from subhumid or drier provinces at the base of the mountains to humid and sometimes superhumid above. The highest mountains even include the temperature provinces in consecutive altitudinal bands—the taiga, tundra, and perpetual ice and snow. The seasonal distribution of precipitation is even variable in this mountainous territory. The land west of the Sierra Nevada and Cascade Ranges is typified by wet winters and dry summers. The whole series of moisture provinces is represented, from the arid deserts of northwestern Mexico to a superhumid strip running from coastal northern California to southern Alaska.

Of the temperature provinces, only the taiga supports trees. It forms a band nearly 1,000 miles wide across the continent in Canada and extends far to the south along the higher mountain ranges. The taiga is a humid province, but the soil and soil water are typically so cold that trees have difficulty extracting it. Water therefore is available only slowly to trees of the taiga even though abundant in the soil. Only trees which can get along on relatively little water can live there.

Three general kinds of trees make up the forests of the North Temperate Zone, including North America: Broad-leaved deciduous trees; conifers; and small broad-leaved evergreens.

The broad-leaved deciduous trees, such as oaks and maples, require the most moisture. They occupy the superhumid and humid provinces that have a moist atmosphere and precipitation evenly distributed throughout the year. The conifers tolerate more hardship. They dominate superhumid and humid provinces in which the precipitation is concentrated in winter, parts of the humid and even subhumid provinces that are too dry for the deciduous broad-leaved kinds, and the taiga province. The broad-leaved evergreen trees of the North Temperate Zone are small trees, with thick, small, and often

sparse leaves, such as the California chaparral. Uniquely adapted to dry environments, they live in subhumid environments.

The humid province of the east, with its uniform moisture supply throughout the year, is especially favorable for broad-leaved deciduous trees. It is occupied by the largest continuous forest of its kind in the world. It is also rich in different kinds of trees, including more than 30 species of oaks.

The composition of the deciduous forest changes from south to north, however. In the south it is dominated by oaks, chestnut, and yellow poplar but contains many others that require a long growing season. Northward and inland, species that tolerate a shorter growing season and more cold are dominant. First come shorter-season oaks and hickories, and then farther north, birches, beech, and maples. In keeping with a universal general rule that the more hospitable environments support a richer mixture of tree species, the number of species that make up the forests of the eastern humid province decreases from south to north as temperatures become less favorable. The forest changes to the spruces and the firs of the taiga province near the Canadian border.

Interspersed with the broad-leaved deciduous forests of the humid province, usually on the infertile soils, are forests of pine. The most notable is the great southern pinery, which occupies the southeastern coastal plain from New Jersey to eastern Texas. Because of the infertility of the sandy coastal-plain soils, the pines have been able to hold this large region even though it is in a climate that favors the broad-leaved deciduous trees.

The forests of the Intermountain West, lying between the Rocky Mountains and the barrier formed by the Sierra Nevada and the Cascade Mountains, are composed of conifers. It is too dry for broad-leaved deciduous trees. Different kinds of coniferous trees are found at different elevations because the climate changes with elevation.

The altitudinal succession of forest types on the mountains of Arizona and New Mexico has been studied thoroughly by G. A. Pearson (*Forest Types of the Southwest as Determined by Climate and Soil*, Department of Agriculture Technical Bulletin 247, 1931). He concluded that deficient heat set the upper limits and deficient water the lower limits where different species could grow. He reported the minimum moisture and heat requirements for four forest types: Pinyon pine and juniper woodland (5,000 to 7,000 feet) 12 to 16 inches of precipitation and average maximum air temperatures for June to September of 78° to 81° F.; ponderosa pine (7,000 to 8,000 feet) 20 inches and 70°; Douglas-fir type (8,000 to 9,500 feet) 24 to 26 inches and 60° to 62°; and for Engelmann spruce and associates (9,500 to 11,500 feet) 30 inches and 57° or 58°.

The forest types studied by Mr. Pearson are extensive throughout the Intermountain West. But in moving northward from Arizona and New Mexico, each type is found at successively lower elevations to conform with the reduced heat and greater effectiveness of precipitation that accompanies the change in latitude. The pinyon-juniper woodland ends in central Wyoming, southern Idaho, and central Oregon, and the ponderosa pine ends in southernmost Canada, both because of inadequate heat. This trend continues to the Arctic Circle, the last outpost of the spruce-fir type of the taiga province. In northern Idaho and western Montana, the most humid part of the intermountain region, forests of western white pine and western larch are able to replace Douglas-fir. And scattered throughout the northern intermountain area are forests of lodgepole pine, which pioneer on recently burned lands or occupy indefinitely some soils in the ponderosa pine and Douglas-fir climates that are unsuitable for the other species.

West of the Sierra Nevada and the Cascade Mountains, vegetation changes strikingly from arid Lower California

to the humid and taiga climates of the high mountains and the super-humid strip along the northern coast.

Chaparral, composed of scrub trees and brush having broad but small, thick, evergreen leaves, occupies the driest of the forest environments, mostly in the subhumid province. Above and north of the chaparral, sugar pine and ponderosa pine intermix to form the most productive and valuable of the western pine forests. These occupy the humid province in the mountains of California and part of southern Oregon. In Oregon the pines meet the great Douglas-fir forests, which occupy the humid and superhumid environment of the Pacific Northwest.

The west coast form of Douglas-fir is different from the Rocky Mountain form. It will not grow in the Rocky Mountain environments. West of the Cascade Mountains, where the wet season may last 8 or 9 months, it forms one of the world's most productive forests. The coastal Douglas-fir forest is often termed a rain forest. It will grow with as little as 30 inches of rain annually, but it makes its best growth where precipitation is much greater and where the atmosphere is continuously humid.

In the superhumid fog belt along the immediate Pacific coast is an extremely lush forest of giant trees. From San Francisco to the Oregon border is the realm of the magnificent redwoods. North of the redwoods and extending to Coos Bay, Oreg., is the home of the little known but very valuable Port-Orford-cedar. And all along the coast, but increasingly as one goes north, Sitka spruce and western hemlock form fast-growing, aggressive forests intermixed with Douglas-fir. The redwoods and Douglas-fir share with Australian eucalypts the distinction of being the tallest of trees. Port-Orford-cedar is the largest species in its genus; western hemlock is the largest of the American hemlocks; Sitka spruce is the world's largest spruce; and another tree of this well-watered land, western redcedar, is the world's largest arborvitae. This forest of giants is made possible by the copious winter precipitation and the summer fogs, which hold transpiration to a minimum.

Because of the warm Japanese current along the shores of the Pacific, the taiga forest of spruce and fir extends northward above the Arctic Circle more than 15 degrees of latitude farther than it extends on the Atlantic coast. But the spruces and firs of the far north are not strangers farther south. They follow the taiga climate of the high mountains southward to the Georgia State line in the Appalachians, to New Mexico and Arizona in the Rockies, and past central California in the Sierra Nevada. They seem to have found and occupied all humid environments that are too cold for other tree species.

FORESTERS AND OWNERS of woodlots can sometimes favor the kinds of trees they want and change the rate of growth of timber by changing the amount of soil moisture in the woods. Tree seedlings are frail things and, lacking the deep roots of adult trees, can be quickly killed by too much or too little moisture in the top layers of the soil. Because to do so is easier, the forester depends on manipulation of soil moisture in the upper layers, rather than the deeper layers, to control species composition and growth rate of forests. He most often works with tree seedlings, and with forests at the time seed that will grow into the next generation of trees is being shed, because then moisture is most critical.

He can, of course, control soil moisture most easily when tree seedlings are raised in nurseries and later transplanted to the woods. Nursery-grown southern pine seedlings, for instance, need about an inch of water a week during their first summer, and nursery sprinklers can be turned on if less than that amount of rain falls. Weeds that compete with tree seedlings for moisture in nursery beds can be pulled by hand or killed by chemicals.

Then when transplants are set out in

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the forest, drought-resistant species can be selected for dry soils and moisture-loving ones for swampy places. Tree-planting experts in the Lake States, in the South, and elsewhere recommend distinctly different kinds of trees for moist and dry areas. Shelterbelts and windbreaks will grow in the naturally treeless Plains only because especially tough kinds of trees have been found that can stand hot, dry winds and live with very little moisture. Drought-resistant trees have been sought all over the world, and now Siberian elm and Russian-olive are almost as common in the shelterbelts as native cottonwood, hackberry, and juniper.

Seeking out the areas with suitable amounts of soil moisture for planting is a good way to increase chances of success. Jack pine does unusually well when seeds are sown on sandy soil with a permanent water table only 2 to 5 feet below the surface. In contrast, the drier, better drained sites in the low-lying Atlantic Coastal Plain should be chosen for planting southern pines.

It is often necessary to prepare land for tree planting by getting rid of brush and weeds that would rob the young trees of moisture. Workers in the Lake States have concluded that planting trees without ground preparation is usually wasted effort. Furrows are plowed where trees are to be planted, or disk harrows are used to kill the grasses, weeds, and shrubs. Hybrid poplars planted in sod do poorly because they cannot compete with grass for moisture. Many are killed outright. Those that live may grow only one-third or one-half as fast as others on land where sod was scalped off before planting. Turning the sod under gives an added advantage through some "fertility effect," which may be partly due to the ability of rotting sod to hold water like a sponge.

Trees planted in regions of low rainfall must be cultivated until they have grown big enough to shade out the weeds that would take moisture from them.

E. N. Munns and Joseph H. Stoeckeler, in the Journal of Forestry, volume 44, page 249, 1946, described the condition of shelterbelts planted by the Prairie States Forestry Project and concluded: "Adequate cultivation is the most important single factor in determining success or failure of tree planting in the Plains."

Harold F. Scholz (in Department of Agriculture Circular 344, 1935) emphasized the importance of every drop of water to trees in the Plains region in these words: "In an area such as this, which receives only 16 to 18 inches of rainfall normally, any year which is appreciably below the average may be considered a drought year. The balance is so critical here that unless the distribution is such as to favor vegetation during the growing season a shortage in precipitation of even 1 inch in a year may have marked effect on trees, and in any event is likely to cause some depletion of the small supply of moisture in storage in the ground. In the case of a wheat crop, the first year of shortage might seriously reduce the yield; if the drought were to persist, the wheat crop might be abandoned for a year and the moisture condition be more or less 'caught up' by fallowing. No such thing is possible with the individual tree or grove of trees."

In other parts of the country where rainfall is plentiful, young tree plantations may still need help. There the moist climate may promote dense growth of perennials and shrubs already established on the planting site. They must be kept cut back until the trees have recovered from the shock of transplanting and have pushed their roots down below the layers where the weeds and bushes can compete with them for moisture.

Young stands that have come up naturally without planting need care and tending, too. Spacing the trees farther apart by thinning makes them grow faster. Some of the benefits of thinning must be due to the larger share of moisture appropriated by the

trees left standing. Furthermore, after thinning, more snow and rainfall can reach the ground, because less of it is held on the branches and leaves to be evaporated back into the air.

But the forester needs most to use his ingenuity when natural reestablishment of forests is to be encouraged following the harvesting of mature trees. Then he must remember what he knows of the normal succession of forests: How, within the limits of the climate and if left alone long enough, dry forests, by their shade and by the damp humus they build up, become moister; and wet forests, by using great quantities of water to grow and by filling lakes and marshes with dead leaves, twigs, and wood, become drier. So it is, he remembers, that gradually over the years, if Nature takes her course, broad-leaved forests may take the place of pine forests and spruce bogs may eventually become birch and maple forests.

Note that moisture seems to control this natural succession, and that over the centuries, or the millenniums, all forests if undisturbed will approach a condition of medium moisture as nearly as is possible within the limits imposed by climate. That is, they will approach the climax forest for the region—a forest composed of trees with water demands as near the mean (as nearly mesophytic) as is possible with the rainfall and temperatures that prevail.

This approach to the climax forest proceeds only in undisturbed forests. Earthquakes, floods, and geologic upheavals can destroy forests and interrupt natural forest succession or start it all over again from the beginning. The forester has to use gentler methods, but he can speed along natural succession, arrest it, or set it back by the way he harvests timber.

Partial cutting—the harvesting of a tree here and there in the woods—results in little change in soil moisture, because enough trees remain to shade the ground and to moderate the wind. The removal of big, old trees may even quicken progress toward the climax by making the turnover faster than it would be if the old trees stood until they died natural deaths. Consequently the forester uses partial cuttings in forests at the climax or near it, if the species are useful for timber and he wants to perpetuate them. Northern hardwood forests of maple, birch, and beech are an example. Partial cutting in them provides the cool, moist shade needed for germination and establishment of these valuable species. Spruce-fir forests are another example. In the drier parts of their range, forests of ponderosa pine also are near the climax of natural succession and they seem to reproduce best under some form of partial cutting.

Many of our forests are farther down the scale in natural succession. That is true of Douglas-fir and of a number of species of pine—notably the southern pines. Seeds of those species generally do not germinate and grow well in the shade of the parent trees. If left alone, more mesophytic forests would eventually replace these pine and the Douglas-fir stands. Therefore, except for single trees or patches of trees left to furnish seed, the forester cuts them clear at harvesttime. When the overhead shade is removed, sun and wind are free to act on the soil and to dry it out. Full sunshine favors germination and growth of young pines, and usually the soil moisture in the exposed clear cuttings is sufficient to sustain them. Thus the violence of clear cutting is used to arrest natural succession toward moister forests, and the valuable pines and Douglas-fir are perpetuated.

Moisture in the upper layers of the soil is critical in the establishment of seedlings in the forest, just as it is in the nursery. The layer of litter and humus on top of the ground dries out more rapidly than the soil beneath, especially following clear cutting. Removal or breaking up of this layer is often necessary so that seed will fall on soil where sufficient moisture is retained for germination and rapid growth of the young trees. It may also

be advantageous because it gets rid of small ground-cover plants that would steal water from the young trees. Furthermore, young trees that germinate in humus seem inclined to form shallow root systems within the humus layer and will be killed when it dries out. Young trees in mineral soil more often develop deep roots that can find moisture in the lower soil layers when the upper ones have dried. Logging, especially when it is done with tractors, will break up the litter layer over a part of the cutover area. Various kinds of plows and harrows have been used to stir up, or scarify, the forest floor. Athens-type disk plows, for instance, have been used with success in stands of jack pine.

Sometimes the forester can use fire to prepare a favorable seedbed. Plant ecologists surmise that most of our fine stands of pine originated when old forests were burned over. They believe it will be hard to perpetuate some of the southern pines, lodgepole pine, and even Douglas-fir without fire. Its use to consume leaf litter and trash that interfere with tree seeds and seedlings has been so successful in the South that research men are experimenting with it elsewhere. Soon foresters may be depending on the good that fire can do; but they will always be fighting to keep it from doing harm.

Those are some of the ways that soil moisture in the forest can be modified indirectly by modifying the forest itself. More direct methods can be used. The draining of swamps to make them capable of growing more valuable timber crops has been tried in this country. It seems to have been more successful in Europe.

The possibility of modifying soil moisture by doing something about the weather is not so remote as it used to be. Suppose it were feasible to predict the occurrence of a wetter-than-usual season in the semiarid Southwest. Then foresters could concentrate their harvests of ponderosa pine timber and their seedbed preparations at a time when the resulting young tree seedlings would have the best chance to grow. Or suppose we could make it rain. One good shower produced at the critical time when the tree seeds are germinating might establish a forest that could grow the rest of its life—perhaps 150 years—without extra help.

Like any other crop, timber cannot grow without water, and like any other crop it needs water at the right time and in the right place.

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How To Get More Snow Water from Forest Lands

B. C. Goodell and H. G. Wilm

Throughout the snowy regions of this continent, deep snow and forests exist together. Exceptions are mountain areas above timberline and crop and pasture lands of the East, where accumulations of snow may be heavy in the absence of forests. But even there, the snow tends to drift with the wind into nearby forests, leaving the open areas bare of snow.

There is, indeed, a relationship between snow and forests: The snow provides winter protection to young trees and abundant moisture in spring and early summer, and the forest in its turn affects the accumulation and melting of snow in many ways.

The close association of forests and snow, together with the importance of snow as a source of water, have led to extensive study of ways by which forests affect snow and supplies of snow-water—effects beyond the simple retardation of drifting.

Consider, for example, that snow may be affected by the density and kind of forest cover. Forests may be made less dense by thinning and more dense by planting or other treatments that encourage natural seeding and growth of young trees. Different species of trees may be substituted for those present; evergreen conifers may be replaced by hardwood trees, and vice versa. Patterns may be created in the forest, with strips of mature trees interspersed with strips of young trees and other strips of seedlings. Openings of any desired size may be cut into the mature forest if such openings will favor the increase or better control of snow-water. All of these things may be done as modifications of the usual processes of caring for and harvesting the timber crop, with the particular purpose of improving water supplies.

As an extension of these thoughts, snow stored in forests bears a close relation to water yields in streams. The effect of this snow blanket is expressed in the spring freshets that characterize streams throughout the northern latitudes and higher altitudes of our country. After a winter period of low, steady flow, streams begin to rise when the snow begins to melt. The resulting rates of streamflow, building up to a high peak late in the spring, are commonly the highest of those produced throughout the year.

As compared to the western mountain ranges, snow is a smaller fraction of the total yearly precipitation in the north-central and northeastern parts of the country. Still, in combination with early rains it contributes heavily to the spring runoff of streams. In the northern Lake States, New York, and New England, one-fifth or more of the annual precipitation comes in the form of snow; and the yearly water from melting snow forms an even higher fraction of the total yield.

In some respects, the storage of water in a snow pack can be compared to that in a storage reservoir. Often it is held in reserve until spring: One to 3 or 4 acre-feet of water per acre of land, or even more, may be stored in a winter snow cover, awaiting release by warm weather. But then the melting snow gives forth its water in a massive surge of streamflow, whose rate and the volume are regulated only by the amount of snow and the spring weather.

Water in a reservoir can be controlled by opening a gate when water is needed and closing the gate when the need is past or the flow is damaging. Water in the snow-pack "reservoir" cannot be so directly controlled, in amount or in time. For that reason, manmade storage reservoirs generally serve a valuable function in the final regulation of water yields from forested watersheds.

At the same time, it appears feasible to exert some indirect control over water yields through the management of forest cover on watersheds. It may even be possible, in fact, to increase the total yield from a watershed—something that reservoir regulation cannot accomplish.

Much research has been done to see how forest management can be used to regulate the yields of water from snow and how treatment of forest cover can increase snow-water supplies and affect their rate of release.

Measurements of the storage and melting of snow in many places and for many years have shown how these variables are influenced by the type and condition of the forest.

Studies of climate within and outside forests have shown how the weather factors that control snowmelt are themselves affected by the forest. As a result, a considerable volume of knowledge has been accumulated on how forests and forest uses influence water supplies from snow: Especially through their influence on the interception of falling snow, on evaporation from the

surface of a snow pack, on melting rates, and on water yields themselves.

THE INTERCEPTION of falling snow on the forest canopy—the needles or leaves and branches of trees—is perhaps the most significant effect of forests on supplies of snow water. The trees offer a canopy on which a sizable fraction of the falling snow becomes lodged and kept from immediately reaching the ground or snow-pack surface.

The snow need not be wet and sticky for interception to occur. Dry snow, by reason of the feathery form of the flakes, will also adhere to the tree crowns. Dry snow has even been observed to build up to a height of several inches on a metallic knife edge and remain there for several hours. The branches, twigs, and needles of coniferous trees offer more secure lodging to the falling flakes and retain snow against even a moderate wind. Many times retention is aided by slight melting and later freezing of the snow in close contact with the tree foliage and bark, although that is not necessary to prolonged retention if strong winds do not follow the snowfall. The feathery flakes cling to each other even better than to the tree foliage.

This interception of snow by trees, particularly coniferous trees, is often observed by people in snowy regions. Not all people realize, however, how long the snow may be retained on the trees and what eventually happens to the intercepted part of the snowfall.

Clear, dry weather with little or no wind often follows snowstorms. Then conditions are particularly favorable for evaporation of the snow (more properly called sublimation when the change is directly from the solid to the gaseous state). The snow on the forest canopy, spread out throughout the height of the tree crowns, is exposed on all sides to evaporation losses. If, instead of being retained on the trees, this snow had fallen to the ground or snow-packed surface, it would present much less surface to the weather elements. It would also be more shaded against sunlight and sheltered from drying wind. Interception and dispersal over the forest canopy thus induce much more evaporation than would otherwise occur.

Even when winds are strong enough to dislodge the new-fallen snow, evaporation losses may be heavy. If the weather stays cold so that the snow remains light and dry, wind often lifts snow from the canopy and disperses it like a smoke cloud high and far into the air. On a clear day much of this snow, with turbulent air surrounding every particle, must turn to vapor during its passage before it can settle again on the tree canopy or on the snow pack.

Warm weather after a snowstorm may cause the intercepted snow to slip from the tree crowns to the snow pack or drip away as snow water. Even then, however, evaporation may still be appreciable: Partly because of the warmer temperatures, water films evaporate more rapidly than snow does.

Losses of snow from forest canopies by interception, evaporation, and sublimation have never been measured directly and probably cannot be. The results of such losses have been determined many times, however, in many places and under various kinds and conditions of forest cover. Interception by hardwood forests and the consequent losses are small because of their leafless condition in winter. Conifer forests, which keep their foliage through the winter, intercept a larger fraction of each snowfall and hold it exposed to evaporation and sublimation. Since the remaining snow passes through the canopy and accumulates as a snow pack under the forest, indirect measurements of interception losses can be obtained by measuring the amounts of snow stored under forests.

One of these investigations was conducted in the Rocky Mountains of Colorado, at an elevation of about 10,000 feet. Four years' measurements after removal of all mature lodgepole pine of merchantable size (more than

9.5 inches in diameter) from several scattered, 8-acre plots showed an average increase of 3.8 inches of water in the snow pack—an increase of 29 percent. Removal of half of the merchantable timber from other similar plots gave an average increase of 1.7 inches in the winter snow accumulation, or nearly half as much as did the heavier cutting. In the same general area the thinning of dense, young stands of second-growth lodgepole pine resulted in an average increase of 2.0 inches, or 20 percent. This thinning reduced the density of the young lodgepole pine stand to about one-half of the original density.

In another study in Colorado, the accumulation and melting of snow under dense young lodgepole pine were compared with the same variables under leafless aspen and in a nearby open area. Fully 30 percent more winter snowfall was accumulated in the aspen than in the stand of young lodgepole pine.

As E. G. Dunford and C. H. Niederhof commented: "This indicates that the thick and closely spaced crowns of the young pine captured much of the snow and allowed it to be evaporated back into the air from the numerous needle and twig surfaces. Aspen, on the other hand, devoid of leaves in the winter, offered only negligible obstruction to falling snow and perhaps reduced the snow-surface evaporation. . . ."

Joseph Kittredge found that 13 to 27 percent of the winter snowfall in the California mountains was intercepted by the coniferous forests and dissipated by evaporation, the largest losses occurring from the most densely forested areas. In a study in New Hampshire, W. L. Maule found similar results. The snow that reached the ground was less under the denser forest stands. Under a leafless hardwood forest, the snowfall to the ground was only slightly less than that in an open area.

The amount of snow loss caused by interception and evaporation naturally varies as the weather changes from year to year. It also varies from one place to another even under forests of similar density. The nature of winter snows, the frequency and kind of storms, and the kinds of weather following storms affect the amount of snow loss. Losses in central Colorado were found to be greater during unusually snowy winters and smaller when the total snowfall was low. It was indicated, however, that such losses might have a ceiling, which would not be exceeded even during winters of excessive snowfall.

There is logic in this pattern of interception and evaporation, varying with the general character of the winter weather. Interception losses in unusually dry winters would be low because the forest canopy would be bare of snow for a large part of the time. With increasing winter precipitation, the number of snowstorms and the number of occasions when intercepted snow could be returned to the atmosphere would both increase. Interception and evaporation would reach a maximum during winters when frequent, light snowstorms are quite evenly interspersed with periods of clear weather. Beyond this point, heavier winter precipitation would mean longer and heavier storms, with smaller and fewer periods of clear weather between them. The most extreme would be "a winter of the blue snow." With storms occurring almost constantly all winter, there would be little loss of snow from evaporation or sublimation. Interception would be only a small part of the total snowfall, because beyond a given volume the trees could hold no more. Without any clear, dry weather, evaporation could be only small in volume.

But the effect of forests in reducing the fall of snow to the ground is not their only influence on snow-water supplies. Forests also affect the snow pack as it lies under the canopy, and may have a decided influence upon its melting in warm "thaw" periods during the winter and spring.

Evaporation occurs from the snowpack surface as well as from the snow lodged in the tree canopy, although at a slower rate. While the forest favors evaporation losses from snow deposited on its canopy, it shelters the snow on the ground and keeps the evaporation losses smaller than losses from the snow surfaces of open areas. The snow is kept under shade, and air temperatures at the snow surface are less than on similar open areas. Wind movement over the snow pack is reduced, so that there is less tendency for the snow to be stirred up and transported into drifts; that also means less evaporation or sublimation.

Methods of measuring snow evaporation accurately have not yet been developed, so that only estimates of forest effects are available. Measurements taken in pans from November to March in the Lake Tahoe region of Nevada indicated the total amount of water evaporated from snow in an open meadow to be 8.5 inches; in a semiopen pine forest, 4.8 inches; and in a small glade in a forest of fir, 2.4 inches. The winter and spring evaporation from snow under a virgin pine forest in Colorado was estimated at 0.8 inch; and 2.0 inches were estimated to have been lost from forest areas where all of the merchantable, mature timber had been cut. Thus, the combination of logic and even these sparse figures indicate little question that forests reduce evaporation from the snow pack.

Forests also reduce snow melting by influencing local climate. This influence is the same as that exerted on evaporation from the snow pack: Forests shade the snow, catching the sunlight and converting it to long-wave radiation, or heat. Much of the radiated heat goes back into the atmosphere, only a part reaching the snow pack. Probably forests also retard snow melting by slowing down the movement of air. The condensation of moisture from the air onto the snow surface releases heat that contributes to snowmelt, and warm air itself causes some melting. By reducing the movement of warm, moist air the forest helps to reduce the rate of melting of snow.

Snow lasts longer in forests than in adjacent open areas. In Nevada, J. E. Church found that the snow pack lost 0.33 inch of water a day in the open, and only 0.20 to 0.23 inch a day in densely forested areas. In the Cascade Mountains of Washington, A. A. Griffin found snow within a dense forest as long as 42 days after all the snow was gone from open areas. The last remaining snow was found in small openings in the dense forest, where snow accumulations had been greatest and shading was complete.

In the experiments in lodgepole pine in central Colorado, snow-melting rates were found to be much more rapid under heavily cutover stands than in the virgin forest. These faster melting rates were offset by greater initial snow packs, so that all the experimental plots became bare of snow at approximately the same date.

Thus available information on snow accumulation, evaporation, and melting rates shows that the effect of forests on supplies of snow water is not simple. Forests reduce the amount of snow that reaches the ground under their canopy. On the other hand, forests reduce the rates of evaporation and sublimation from the snow pack. By retarding the melting of snow, forests may cause some snow to remain later in the spring. That effect results in a longer duration of snowmelt streamflow, but it also favors greater evaporation losses by leaving the snow and snow water longer exposed to the air.

The overall effect of forests on snow-water yields to streamflow has been accurately shown in this country by only one study. Near Wagon Wheel Gap in Colorado, the streamflows from two small watersheds were compared for 8 years. Both watersheds were covered with forest and were left undisturbed during that time. The

forest cover was light on both areas, however; only about one-half of each area was covered with conifer trees, the remainder being in aspen or in grass. Thus the effects of the forest cover on snow accumulation, losses, and melting rates could be no more than moderate at best.

After the first period of comparison, one watershed was cleared of all standing trees, and the comparison was continued for 7 more years. As a result, the average yearly streamflow from the treated watershed was increased 16 percent during the 7-year period. The increase was greatest in the years immediately after the cutting, diminishing with regrowth of the forest but still existing at the end of the period. Nearly every month in the year showed an increase in streamflow, but the greatest difference was during the spring snowmelt period. Most of this was doubtless caused by the elimination of losses of snow from interception on the tree crowns, which more than offset increases in evaporation from the snow-pack surface caused by removing the shelter of the forest.

Other effects of the timber removal were an increase of about 50 percent in the streamflow peak, and its advance to a date about 3 days earlier than the average date of peak discharge before treatment. The more rapid flow of snowmelt water and disturbance of the soil caused by logging and the burning of brush resulted in somewhat more erosion from the cutover area.

The Wagon Wheel Gap experiment illustrates how snow water is affected by the complete but temporary destruction of forest cover. It represents a type of forest treatment that would not be safe to apply on most watersheds. At Wagon Wheel Gap, damage was small because the soils of the watershed are porous and allow snow water and rain to penetrate readily. Accordingly, surface runoff and the accompanying soil erosion were minor even after the destruction of the protective forest mantle. In areas of less permeable soil or less gentle climate, serious erosion might easily have resulted, with a consequent impairment of the quality of water. Commercial forest values were also sacrificed in the demonstration. Especially if the watershed had been kept denuded in order to maintain maximum increases in streamflow, timber production would have been permanently eliminated. Thus the study compared the effects, good and bad, of the complete removal of forest cover, but it left undetermined the effects of forest management practices designed to favor timber production and soil protection as well as yield of water. Even from the standpoint of water yield alone, maximum benefits and minimum damage would depend upon adequate reservoir storage downstream of the treated watersheds.

Increasing snow-water supplies while still favoring timber production and soil protection is the object of studies now under way. An accompanying goal is to learn how the water increase can be spread as well as possible into the summer months of high demand for water. On one watershed in the Colorado mountains, mature lodgepole pine and spruce timber are being harvested in a stripwise pattern. Long strips, 66 to about 400 feet wide, have been laid out over the whole area. Strip directions thus range from north-south to east-west, on both moderate and steep slopes. All the timber on alternate strips is being cut and removed over an intricate system of logging roads.

The study is expected to reveal the increase in yield of snow water caused by harvesting one-half of the timber from a watershed and also how the accumulation and melting of snow are affected by the direction and width of strip. Where the orientation of the strips results in shading of the cutover land during the warm part of the day, rates of melting may be little greater, if any, than under the uncut forest itself. It may also be found that snow

will drift from the wider, cutover strips into the adjacent uncut strips, where it will be protected against rapid evaporation loss and melting. The pattern and extent of cutting applied in this experiment are practical from the viewpoints of timber production and soil protection as well. Any resulting benefits to water supplies thus will add to, and not supplant, other forest values.

In some regions where there is special need to increase snow-water supplies, conversion from conifer to hardwood forests may be desirable. Commercial values expected from the conversion of hardwood to conifer forests may be more than offset in other areas by reductions in water yield. Certainly a hardwood forest cover would be expected to intercept less snow than a conifer forest. Attention would have to be given, however, to whether the hardwood forest would use more water during the summer. Soil and root depths have important roles in this problem, and the particular watershed and the hardwood species to be employed would have to be studied before the overall benefits could be estimated. These are problems of growing magnitude in the northeastern United States. Practically no research results are available yet to indicate what may be the best management of forested watersheds for both water production and wood products.

Patternwise harvesting of timber, conversion of evergreen forests to hardwoods, thinning of overly dense young stands—those are some of the tools by which snow-water supplies may be increased through forest management. Research has shown that forests affect snow-water supplies in important but complex ways. We need now to learn whether increased yields can be obtained without the harmful effects of excessively rapid and early snowmelt. We also need to learn much more on how management for additional water supplies can be combined with management for good timber growth and soil protection. Blanket rules cannot result from such research, but we hope that general principles can be developed, on the basis of which every land manager can determine the best procedures for his own watershed. Soil, topography, climate, and forest characteristics all have their parts and must be considered in plans designed to get maximum benefits from our forests and snowfields.

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Managing Forests To Control Soil Erosion

E. G. Dunford and Sidney Weitzman

Undisturbed forests are notably resistant to the inexorable wearing down of the earth's surface. The rates of soil development in them generally exceed the slow process of depletion, but the rates of erosion rise inevitably on the heels of activity of man and Nature. How well the job of watershed management is carried out determines how high and how fast the rates rise.

A manager of a watershed deals with all the resources of a drainage, but his primary aim is to utilize them in such a way that maximum quantities of clear, usable water are achieved. The watershed manager does not have to be a specialist with a single purpose. He can be a logging superintendent, a rancher, a tree farmer, or a forest ranger. It is essential, though, that he include control of erosion in his plan of management and that he think of water and soil as resources of value like trees and forage.

It is not a simple task to keep the soil intact on a forest area while the timber is being logged and the forage is grazed. Yet that is the challenge that the watershed manager must face. Locking up a drainage to minimize erosion is a solution with only limited application. The more practical doctrine is maximum use of forest products within the limitations imposed by sensible control of erosion.

It is the watershed manager's job to learn what the limitations are, what methods are required to meet them and where they should be applied, and what are the basic causes of erosion.

The primary cause is water moving over the surface of the ground. Severity of erosion, in turn, is determined by how much water is moving, how fast it travels, and how readily the soil can be picked up and carried. Control, on the other hand, depends on how fast surface water will soak into the soil, how effectively its speed can be slowed by obstructions, and how well the soil particles can be protected by vegetation. An undisturbed forest best exemplifies the controls that operate most effectively.

In an undisturbed forest, water from precipitation is dispersed into the air or is led to streams and underground storage in a gentle, undestructive manner. Surface runoff does not occur except during periods of prolonged and heavy rainfall.

Vegetation and soil are chiefly responsible for this stability. Vegetative control begins with the protective canopy of trees and underbrush. Some of the falling rain and snow is caught by the crowns of trees and does not even reach the ground. Vegetation may also break the force of the rain so that drops reaching the forest floor are less capable of detaching the soil particles and washing them away. Litter and humus provide additional barriers against the flow of surface water and aid the soil by increasing its porosity. Water readily filters into a forest soil without accumulating on the ground surface.

A WATERSHED MANAGER strives to maintain this kind of control when forest lands are disturbed by logging, roadbuilding, and grazing. In forest lands already depleted by erosion, he attempts to match the stability of undisturbed forests by employing measures that will allow more water to enter the soil and reduce the velocity and amount of runoff.

His job is complicated, however, by many conditions that influence erosion. Some forest areas remain relatively stable under severe treatment. On others erosion is easier to start and harder to stop. The differences in susceptibility usually can be traced to variations in soil, climate, and topography.

Forest soils are by no means uniform in their characteristics. Coarse and

porous varieties of the glaciated sections in New England, the Lake States, and the Pacific Northwest can absorb fairly large quantities of rainfall. Similar qualities characterize the pumice-covered slopes in parts of the Sierra Nevada and Cascade Ranges. On the other hand, heavier textured clays derived from sedimentary rocks, such as those found in the northern Appalachian Mountains and southwestern Colorado, are easily eroded. Loess soil adjacent to the Mississippi River is highly susceptible to erosion when protective forest cover is removed because it is an unstable product of windblown material.

Shallow soils resting on impervious sloping bedrock will slide more readily than those that are deeply weathered. They also have limited root space and relatively less capacity for water storage. Soils of this type often are sterile. They are subject to erosion because protective vegetation suffers from the lack of plant nutrients and moisture.

Intense rains cause erosion in regions subject to thunderstorms. They are common, for example, in the Colorado Front Range on the eastern flank of the Rockies and in the Wasatch Front of Utah—zones in which total available moisture for protective plant growth is relatively low. Soils of undisturbed sites generally are able to soak in all of the rain as fast as it comes; but the margin of safety is thin and when torrential rains occur, even a slight reduction of soil porosity can cause runoff and erosion.

Heavy and intense rains themselves will result in reduced soil porosity if vegetative cover is not sufficient to break the force of the drops.

Season and kind of precipitation—snow or rain—are also important. For example, precipitation is fairly well distributed throughout the year in the eastern United States. Many severe rainstorms come in the winter when the trees are bare and the soils are saturated. This climate encourages erosion. By contrast, in the high Rockies more than two-thirds of the precipitation is snow. Gradual melt in the spring restores the season's supply of moisture in a deep, natural reservoir of soil and underlying fractured rock. Seldom does the rate of snowmelt exceed the ability of the soil and rock to absorb it.

In regions having open winters, frost presents another hazard. Some kinds obstruct the downward movement of moisture during the spring breakup, and surface runoff follows. If the forest cover is intact, however, frost is less likely to create an impervious barrier, and the soil stays receptive to water. In places like Arizona, South Carolina, and eastern Oregon, needle frost occurs on the surface of soils not protected by good forest cover. The effect is to create a fluffy layer, which is carried off by the next rain. A sample taken in the South Carolina Piedmont showed that 18 pounds of soil per 100 square feet were loosened in one daily cycle of freezing and thawing.

Topography is the third factor that influences susceptibility to erosion.

Forest lands, particularly west of the Mississippi River, are commonly confined to mountainous terrain. The more gentle, timbered slopes of the western regions have been largely cut over, and logging is extending farther up the rugged slopes. It is obvious that, other things being equal, these steep slopes will erode more easily.

The direction in which the slopes are facing is also important. Dry south-facing hillsides are more apt to erode than moist north slopes, particularly in subhumid climates, because vegetation finds growing conditions more severe. Recovery from disturbance is usually slower.

In most forested areas, whether they be virgin stands or restocking cutovers, nature tends to balance out these variables in such a way as to provide maximum control of the soil. In some instances, however, the balance is rather delicate, and failure to recognize precarious areas has led to serious damage.

Many of our forests are traversed by roads and have been cut over and logged several times. Large areas of woodland are heavily grazed, and many acres of forest land have been burned repeatedly.

ROADS ARE NECESSARY in the use and management of forests and rangelands. Yet roads are a major source of erosion. They may expose raw mineral soil and their surfaces resist the intake of water. As travel increases, the roadbed becomes more compact, and infiltration slows to an imperceptible rate. Water runs over the surface and carries away large amounts of eroded material. Gouging into hillsides to construct a road creates new water channels by cutting through natural underground passageways. Instead of flowing into and through the soil at normal rates, water now concentrates in ditches and runs unchecked to the nearest stream channel.

Construction of roads parallel to the stream channel is a particularly poor practice. On steep banks, earth is generally cast downhill—into the stream itself if it happens to be close enough. The destructive effects sometimes are not evident until streamflow becomes high enough to eat away the base of the overcast material, thus causing more to slide down from above. Slides are always a danger when the roads are constructed on unstable ground. Slide areas frequently continue to slump long after the original disturbance takes place.

Present-day trends in road construction introduce possibilities of added dangers from erosion. Requirements for wider roads and better alinement, mean more soil must be disturbed, particularly in rugged terrain.

Furthermore, density of the road pattern will increase as more intensive wood utilization, forest culture, and fire protection are practiced. In the Douglas-fir region, for example, the present requirements for log hauling and protection roads are roughly one mile for each square mile of forest area. These areas may eventually require four miles or more of road to the square mile, thus increasing the chances for erosion.

Logging is one of the most common activities in our forests and one generally responsible for considerable erosion. Two major operations are involved: Cutting the trees and removing the logs by skidding.

Most observers agree that erosion following logging is caused primarily by disturbance from skidding. Dragging logs along the ground by means of horses or tractors has the same effect as roadbuilding. Raw earth is gouged and compacted by repeated trips, which soon create a troughlike trail. Usually skid roads run up and down hill, funneling toward a loading point. They make ideal channels for concentrated flows in damaging proportions.

Skidding is often done in the stream channel, a practice that damages streambanks and creates a longtime problem. Dragging logs through and across a stream breaks down the protective bank vegetation and leaves a mass of debris. The accumulations dam the flow of high water until finally a wash out will carry large masses of the debris downstream, ripping the exposed banks along the way. The process is repeated until a wide scour replaces the original stream bed.

Logging can be most destructive in emergencies that require salvage of dead timber. Wholesale removal following destruction from disease, insect attack, or fire has caused abnormal

amounts of erosion. Salvage after a forest fire is particularly serious because the soil has already been robbed of its protective humus. Coupled with this hazard is the urge for haste to remove dead timber before it decays. Precautions against soil loss are frequently forgotten in the rush to salvage a maximum volume of decay-free timber.

Wild fires set the stage for destructive salvage and in themselves are truly the handmaiden of erosion. Fires burn off the protective vegetation and destroy the water-holding capacity of the humus mantle. Increased erosion and runoff generally follow.

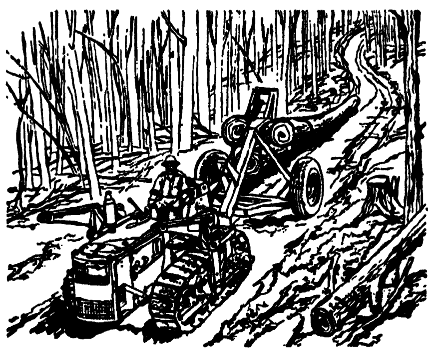
Severity of the erosion following fire is proportionate to the amount of vegetation and organic material removed, the steepness of the slopes burned, and the type of precipitation that follows. Woodland burning does not greatly increase erosion of sandy soils on gently rolling or flat areas in southern forests. But fire on steep chaparral slopes has caused extremely detrimental effects when heavy rains followed. In the San Gabriel Mountains in California, flood flows increased from 20 and 60 cubic feet per second (c.f.s.) per square mile in unburned watersheds to an estimated 1,000 c.f.s. per square mile in a burned watershed. This high flow carried vast quantities of gravel and rock into the valley below.

Grazing can create an additional erosion hazard on forest lands that provide forage for domestic stock and big game. Heavy grazing adds to surface runoff by reducing plant density and by increasing soil compaction from trampling. Palatable grasses and shrubs lose their vigor by continual close cropping, productivity drops, tops and roots die back, and valuable litter dwindles. Original cover is finally replaced by plants less efficient in staving off erosion, and continued grazing eventually exposes dangerous amounts of bare soil.

Other incidental uses, such as strip mining, rights-of-way for powerline construction, campground development, and clearing for ski areas, disturb the forest. All pave the way for erosion because they deplete the protective vegetation and expose soil to direct impact of rain and runoff.

Erosion from roads can be controlled if some present methods are changed. Some suggestions:

1. Plan the road system in advance of construction. It is a practice that



reduces the area of soil disturbances and also lowers costs of construction, maintenance, and hauling. On the Fernow Experimental Forest in the Appalachian Mountains, road mileage was reduced between 40 and 75 percent by careful advance planning. Similar savings were made on the H. J. Andrews Experimental Forest in the Oregon Cascades. In both places it also was possible to take advantage of topography to avoid unstable areas and to reduce soil disturbance in the cut and fills.

One potentially effective planning tool is soil classification. Location of the road system and the measures for preventing erosion should be adapted to the inherent stability of the area. Until we know more about physical characteristics of forest soils and their reaction to disturbance, we will have to rely on very general rules of thumb for guides in building our roads.

2. Learn to recognize and avoid trouble spots. Knowledge of soil and rock characteristics is important in locating roads. Avoid seeps, clay beds,

and steeply dipping rock where slides are likely to occur.

3. Keep the grades low. The Forest Service prefers 7 percent as a general maximum, but exceptions can be made where steeper grades are needed to take advantage of favorable topography or to avoid excessive cut and fill.

4. Provide adequate drainage. Roads are sources and carriers of muddy water. Streams crossing under roads should not be contaminated with surface drainage and ditch water. Culverts, open troughs, and dips for handling surface water should be spaced at frequent intervals and placed so that they drain onto vegetated ground where mud can be filtered out. They should be adequate to accommodate the highest expected flows, taking into account the increased water yield that will result from logging. Frequently it is desirable to "roll" the grade with alternate dips and swells to prevent surface water from traveling long distances in wheel ruts.

5. Do not build a road in or near stream channels. In mountain country a stream bottom or its sloping sides may look attractive, but trouble begins when the road is constructed there. Subsequent skidding and hauling disturb the channel, and it remains a serious source of erosion long after logging ceases. Keep to the benches and ridges as much as possible. Rarely is it good practice to make a roadway in the bottom of swales and other depressions. During spring melt and storm periods surface drainage will collect in the compacted roadway and will gather sufficient speed and volume to begin cutting. Many deep gullies have started in this way.

6. Build with the minimum of earth movement. Deep cuts and extensive fills are not desirable. The road beds should be kept as narrow as safe use will allow. Strive to balance the volumes of earth in cuts and fills. If some earth must be wasted, it should never be dumped near live streams. Build during dry weather.

7. Maintenance is important. While a road is in use, maintenance is required to keep it in repair and to keep cross-drainages open so water will drain off. Fill material and logging slash should not be allowed to plug the upstream ends of culverts. Immediately after logging, temporary roads need to be "put to bed" and allowed to heal. This means that water diversions, cross-drainage ditches, and other means for draining the road are put in order. Seeding with grass will help stabilize raw cuts and fills. If the road has been properly laid out and drained, only periodic checking and cleaning of diversion ditches will be needed to keep it ready and usable for the next logging operation. Permanent forest roads should be surfaced with rock and graded with a center crown to provide for surface drainage. During storms it pays to patrol the roads frequently to keep drainage open.

Erosion from logging can be diminished by improving skidding practices and paying attention to trouble spots afterward. Methods of logging and the equipment used have a tremendous effect on water quality, too. Here are some guides:

1. Do not yard logs along stream channels. Locate landings so that logs are dragged away from streams rather than through or across them. Logging debris should be pulled out of stream channels to prevent damming and diversion of water flow.

2. Keep skid trails well drained by diverting the water into areas where the sediment can filter out. It is especially important that water bars and diversion ditches be installed after logging. Frequent inspection is needed in rainy periods to assure that the drainage checks are controlling surface flow.

3. Do not use tractors on steep slopes or wet ground. Tractor operations should be limited to less rugged terrain and to the dry seasons of the year. As a rough guide, 30-percent slopes are considered a desirable maximum for tractor operation on many types of soil. Soils are considered too

wet when they contain water that can be squeezed out by hand.

4. Adapt logging equipment to logging conditions. On many Forest Service timber sales, high-lead cable logging is specified on steep slopes.

Tractors are more efficient on flat or gently rolling locations. They are frequently used with a logging sulky, dolly, or arch attachment to help ease skidding by lifting the front ends of the logs. The practice also benefits the soil by reducing the amount of gouging. Winch and cable attachments also are effective for reducing soil disturbance; many logs can be reached without going directly to them with the tractor. As a further refinement, skidding full-length trees makes possible a reduction in trips, and a proportionate decrease in the amount of erosion.

Where slopes are too steep for practical tractor operation, west coast loggers employ high-lead and skyline yarding systems. Logs are moved from stump to landing by cables extending from a pulley-block high on a spar tree or swung from a skyline stretched between two spar trees.

As logging progresses into steeper terrain, the problem of maintaining soil stability becomes more serious. Some of the more rugged sections of the Rocky Mountains and Sierra Nevada and Cascade Ranges very likely should not be logged at all by present methods. The Wyssen skyline crane, developed for mountain logging in Switzerland, holds promise for those areas. The device is designed to suspend logs in midair during much of their travel from stump to loading point. Haul roads can be reduced considerably because a relatively large area is reached from a single landing.

5. Seed erosive areas to get a quick cover. Skid trails and landings on unstable soils should be sown with grasses and legumes where natural regrowth is slow. Tree reproduction will have a better chance to return on these sites if non-sod-forming grasses are sown. Cattle should not be allowed to concentrate on reseeded areas, because their trampling may nullify the erosion-controlling effect of the grass. If grazing by both big game and domestic livestock needs to be discouraged for erosion-control purposes, highly palatable grasses should not be planted.

FIRE PREVENTION must be intensified on a national scale. Uncontrolled fires have no place in integrated management. Added effort to control fires will be in the best interest of erosion control, as well as in preventing the waste and destruction of usable forest products.

As one tool in forest management, burning can be practiced under some conditions. Some protective cover is always removed, however, and chances for erosion are significantly increased on sloping areas. It can be kept under control if a few precautions are used:

1. Controlled burning should be carefully supervised always by competent foresters. Even prescribed burning may prevent adequate vegetative recovery, and a progressive lowering of the infiltration capacity will normally result.

2. Do not burn in the dry season. Burning of slash, practiced in the West to reduce fire hazard, should start after the fall rains begin.

3. The economic return from logging fire-killed timber should be weighed against added soil loss. If the timber must be salvaged, precautions against erosion should be intensified—not relaxed.

GRAZING, like timber cutting and fire, is an acceptable watershed practice only if soil disturbance can be avoided. In the East and Midwest, considerable grazing takes place in farm woodlots made up principally of hardwood species. Grazing there benefits neither the animal nor the woods. It is a poor practice from the standpoint of erosion. Grazing on forested areas is common in the South and West in relatively open-grown pine forests and intermixed meadows and

parks. In those sections the following principles apply:

1. Forage should be moderately grazed. Herding, fencing, and use of well-distributed water holes and salt grounds will help avoid concentration of stock and localized overgrazing. Safe carrying capacity of the forage should be determined, and herd numbers adjusted accordingly. Stubble height can be used as a gage for deciding whether enough herbage remains to provide forage for the following year and protection for the soil.

In an experiment on a ponderosa pine-bunchgrass range in Colorado, moderate grazing produced only negligible additions in erosion, but important soil losses followed heavy grazing. Moderate grazing in that area leaves approximately 4 inches of stubble on Arizona fescue, one of the principal forage species. If the average stubble height at the end of the grazing season is 2 inches or less, it is judged that the range has been heavily grazed.

Amounts of ground cover needed to prevent erosion have been determined on aspen sites in northern Utah. Soil loss appears to be unimportant when 5 percent or less of the rain from summer storms runs off the ground surface. To keep surface runoff below this limit, at least two-thirds ground coverage of living plants and litter is needed. Up to 75 percent cover is necessary for the same protection on herbaceous subalpine ranges having heavy soils.

2. Grazing can be very damaging when the soil is wet and subject to compacting. In high forested mountain ranges of the West, it is unwise to permit stock on the range while the soil is still saturated with snowmelt.

3. Frequent inspection of the grazed areas should be made for signs of overgrazing and soil deterioration. Soil damage develops slowly on grazing lands, and it is important to detect it as early as possible.

These recommended measures for roadbuilding, logging, grazing, and burning are aimed at prevention and control. Where they are applied according to the needs of each individual watershed, erosion can be kept within acceptable limits. The need for costly remedial measures in the future will be virtually eliminated.

An occurrence in West Virginia emphasizes the cost of ignoring preventive measures. In October 1954, a mountainous area was hit by a severe local storm. Flood stages reached and exceeded the level of the maximum recorded flood in several places, and damages were high. Immediately afterward an inspection was made of several forested areas to note the source of damage from current and recently completed logging. In places where preventive maintenance measures had been installed and the proper equipment used, the roads, logging decks, and skid trails showed no excessive erosion. In places where inadequate precautions had been taken, the roads, bridges, and culverts were washed out, and in many cases the initial investment was lost.

In one section of northern Mississippi, the original hardwood cover was removed years ago and the area converted to farmland. Soil and climate make the region highly susceptible to erosion. Early signs of impending deterioration, which should have been a warning, were ignored, and 60-foot gullies resulted. The remedy now calls for expensive mechanical controls such as gully plugs, contour trenches, water diversions, retaining walls, and impounding dams. Their purpose is to stabilize soil enough to allow vegetation to become established.

Permanent vegetation will always be the ultimate need for bare eroding sites. On denuded forest and range areas the ultimate goal is return of trees and grass. But there are many cases where a quick cover of a short-lived type of vegetation is needed to hold the soil until more permanent species can get set. In southern California, this has been done by seeding more than 130,000 acres of burned chaparral slopes with black mustard.

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Success has been variable, depending on how well the mustard became established before heavy rains hit the seeded slopes.

WHILE THE WATERSHED MANAGER struggles with the task of rebuilding deteriorated lands, his real challenge for the future becomes clear. In forested watersheds he must find better ways of preventing erosion while the full productive capacity is being utilized.

Many watershed managers visualize this ideal as a drainage that supports a productive stand of trees ranging from seedlings to fully grown timber. A complete and stabilized road system is already built, making it possible to remove salable forest products from harvest cuttings and thinnings with minimum soil disturbance and stream siltation. The road system also permits intensive fire protection as well as access to the area for fishing, hunting, and camping. Near the mouth of this hypothetical watershed the stream may flow through a valley with irrigated farms, several small communities, and a wood-using industry consisting of two sawmills, a pulp mill, and a furniture factory. All are dependent on the watershed for a regulated flow of clean water, a sustained supply of wood products, and a source of recreation.

The watershed manager can help achieve this kind of integrated use if he plans carefully for control of erosion and then skillfully and diligently follows his plan.

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Soil Surveys on Forest and Range Lands

J. L. Retzer and E. A. Colman

The farmer, the grazier, and the forester need information about the productivity of their land if they are to manage it effectively. The information is obtained by surveys, of which there are several kinds.

Land surveys take the forms of maps, which show how the land lies, and reports with information about how it is being used.

Crop surveys, with or without maps, show the kinds of crops being grown, their yields, and the land management practices that are being used.

Soil surveys show on maps the kinds of soil present, the areal extent of each, and the report explains their characteristics and discusses the uses to which each soil is or can be put.

The information supplied by surveys enables the land manager to put each piece of land to its best use, and helps him determine where to apply good practices developed through experience and research.

SOIL SURVEYS are of particular importance to the land manager for two reasons.

First, very roughly the soil may be compared to a bank from which funds

are drawn for the production of crops. The funds take the forms of water and nutrients for plants. From information in modern soil survey reports the land manager can determine whether his soils have good or restricted drainage, and he can obtain some information on the amount of water his soils will hold and the rapidity with which they take up water from rainfall or snowmelt. Soil surveys also provide information about the nutrient level of his soils: Which plant nutrients are in abundant supply and which are in short supply. In addition, and of particular importance to managers of hilly or wild land, soil surveys provide information about the susceptibility of soil to erosion and rapid runoff of storm water.

Second, soils are variable. They differ markedly from place to place in the characteristics we have mentioned. Surveys are needed to show where soils with certain combinations of characteristics are located. A soil survey supplies information that permits the land manager to select areas for certain uses, based upon the potentiality of the soil to produce crops of various kinds and upon the management measures needed to keep the soil in place and productive.

A completed soil survey presents a map and a report. The map shows the location and boundaries of each kind of soil. The report describes the characteristics of each soil and provides information about its usability for crop production and about the measures needed to protect it and keep it productive. With proper interpretation, both the map and the report carry much valuable information that can be used in engineering problems arising in conjunction with road building and other structural work. The report is as important as the soil map, for without it the manager of the land would be at a loss to know how the different soils would respond to treatment.

A uniform system of soil classification must be followed if the information is to be useful. Soil classificational units (soil series) must be defined so that soil differences can be recognized in the same way, regardless of where surveys are made. The soil series is the classification unit now used. As defined in Department of Agriculture Handbook No. 18, the soil series "is a group of soils having soil horizons similar in differentiating characteristics and arrangement in the soil profile, except for the texture of the surface soil, and developed from a particular type of parent material." Within the soil series, two subunits are recognized: Soil types, which differ in the texture of the surface soil; and soil phases, which differ in such characteristics as stoniness, slope, depth, or degree of erosion. This system of classification is used nationwide and thus permits uniform recognition of different soils in all parts of the United States.

Important steps have been taken toward an international system of naming soils. Thus, through soil classification, the research results from other countries are available to us here on similar kinds of soil.

Soil surveys on forest and range lands differ in some respects from those made on cultivated lands. Both generally employ the soil series as the classificational unit, but they usually differ in the minimum size of area which is delineated and in the method used in making the survey. Three reasons exist for the differences.

Cultivated and forest and range lands are managed differently. Cultivated lands are managed intensively; they are plowed, fertilized, and seeded to crops, which usually require care during growth. Areas of 1 acre or less can be economically managed in different ways to insure maximum crop production. The delineation of small areas containing different soils therefore is justified. Wild lands are managed extensively; the main concern is to grow and harvest native crops without cultivation or other soil treatment and to protect the soil from excess erosion and runoff. Because these are managed uniformly in areas much larger than a few acres, the detail used in separating

soils of cultivated lands is not justified. Usually the minimum size of areas delineated in forest and range land soil mapping is between 10 and 40 acres.

Cultivated lands are more easily accessible than forest and range lands. Because cultivated lands are open and easily traversed, their soil boundaries can be mapped with considerable precision. Many forest and range lands have few roads, and many are rugged and remote. The limited accessibility makes the cost of detailed soil surveying prohibitive except in special cases, such as research areas under scientific control. The minimum areas delineated therefore are ordinarily larger on forest and range lands than on cultivated lands.

Forest and range soils often differ in some respects from those of cultivated lands. Many such soils are developed in place from weathering of underlying rocks, and they have not been disturbed by cultivation. The more favorable areas, those with deep soils and favorable topography, are cultivated. Cultivated soils, many of which have developed from materials washed into bottom lands or other low places, have been plowed and altered in the course of crop production. Knowledge of the surface geology often provides important clues as to kinds of soil that may be found in an area, and rock type boundaries often indicate changes in soil types. Often different landforms have different kinds of soil. Valley terraces and steep upland slopes are examples of landforms that have contrasting soils. Landforms provide important clues to the location of soil boundaries which are hard to map in any other way. These are aids to the soil mapper in forest and range lands.

Two techniques have been adapted for soil surveying in forests and rangelands. The first technique is the use of aerial photographs in the office for the tentative delineation of soil boundaries and other features of the landscape. Aerial photographs are valuable in speeding soil survey work in rough country. Landscape differences that are related to soil differences must be detected on the photographs, after which field examinations can be made to check the interpretation of the photograph and to describe the soils in typical areas. Soil boundaries, particularly those coinciding with obvious landscape features, often can be drawn accurately on the photographs and then transcribed to maps.

The second technique consists of the mapping of several features of the landscape in one operation. Soils are mapped; in addition, a map is made of different features of the vegetation. In forests and rangelands it is an advantage to map vegetation types because they are a more permanent part of the landscape than are cultivated crops. A knowledge of the species present and density is important information for the land manager. The mapping of crops is an old procedure used in soil surveys of cultivated lands when crop information is desired for that particular area or year. These combination maps have the added advantage in that relations between soil characteristics and vegetation characteristics can be studied on the ground. The combined soil-vegetation survey is more useful for management purposes than either survey alone, and it has the added advantage of reducing costs.

The use made of forest and range soil surveys can best be shown by examples drawn from surveys that have been made or projected.

A combined soil-vegetation survey of the forests and rangelands in California has been started. The information obtained includes a map and description of soils and a map of forest and range vegetation, with appraisals of site quality—timber and forage productivity—of the various types.

Nearly 4 million acres were covered between 1948 and 1955. As the work progressed, it became increasingly clear that a close relation exists

between kind of soil and kind of vegetation. Certain soils are associated with forests of high productive capacity; others with forests of lower productive capacity. Grasslands of high or low quality are similarly found associated with certain soils. The close relations found enable the forest manager to use the soil survey as a guide in judging the productivity for timber of forest land which has been cut over or burned to such an extent that insufficient trees remain for determining site quality. It enables the range manager to estimate the forage productivity of grasslands whose cover has deteriorated so much that direct determinations cannot be made. And it provides one basis for judging whether brush-covered land can be managed for timber or forage production or whether it would produce so little growth of timber and forage that the effort and cost of conversion to trees or grass would not be justified.

The survey in California can also serve other management needs. For watershed management, information is needed as to the rate at which water can be absorbed by the different kinds of soil, and the rate at which water drains through the soil profile; the quantity of water needed to wet the dry soils before streamflow starts; the erodibility of the soils; and the ways in which those functions are affected by the kind and condition of the vegetation cover. For engineering purposes information is needed regarding the suitability of particular soils for subgrade surfacing material for roads and the tendency of soils to slide when cut through or to wash out when used as fill material. When information of this kind is obtained for representative examples of the more important kinds of soil, it can be extended to large areas wherever the same kinds of soil are found by using the soil classification shown on soil maps.

IN THE LAKE STATES, site quality for timber was found to be related to soil series and soil type. Certain soils, for example, were ordinarily found associated with highly productive stands of white pine; others were associated with pine stands of medium or low productivity.

In east Texas, similar relations were found for loblolly and shortleaf pines. In Washington, differences in site quality for Douglas-fir were found between soils that were recognizably different.

ABOUT 18.6 MILLION ACRES of forest lands and rangelands were mapped in the United States between 1949 and 1955. Some of the surveys were too broad and schematic for maximum usefulness, but they still supply a good deal of information of value to the land manager. The most useful surveys followed standard procedures as to mapping methods, soil classification, and soil examination.

As management of forest and rangelands becomes more intensive, the information obtainable from soil surveys becomes increasingly important. Such surveys, with proper interpretations, provide one of the land-resource inventories indispensable in the proper and adequate planning of land use.

FOR RANGE LANDS they indicate what forage particular ranges can produce, what plants are suitable for revegetation of depleted ranges, and what erosion hazards accompany various kinds of grazing practices. For the brush-infested rangelands they show where and under what kind of conditions brush removal and forage improvement can be done successfully. For forest lands they provide guides for timber-harvesting practices which aid regeneration of the forest and hold erosion low, and they indicate the suitability of particular areas for commercial timber production. For watershed management they enable division of a body of land into classes related to the soil's susceptibility to erosion, its ability to receive, store, and transmit water, and its adaptability to various water control practices.

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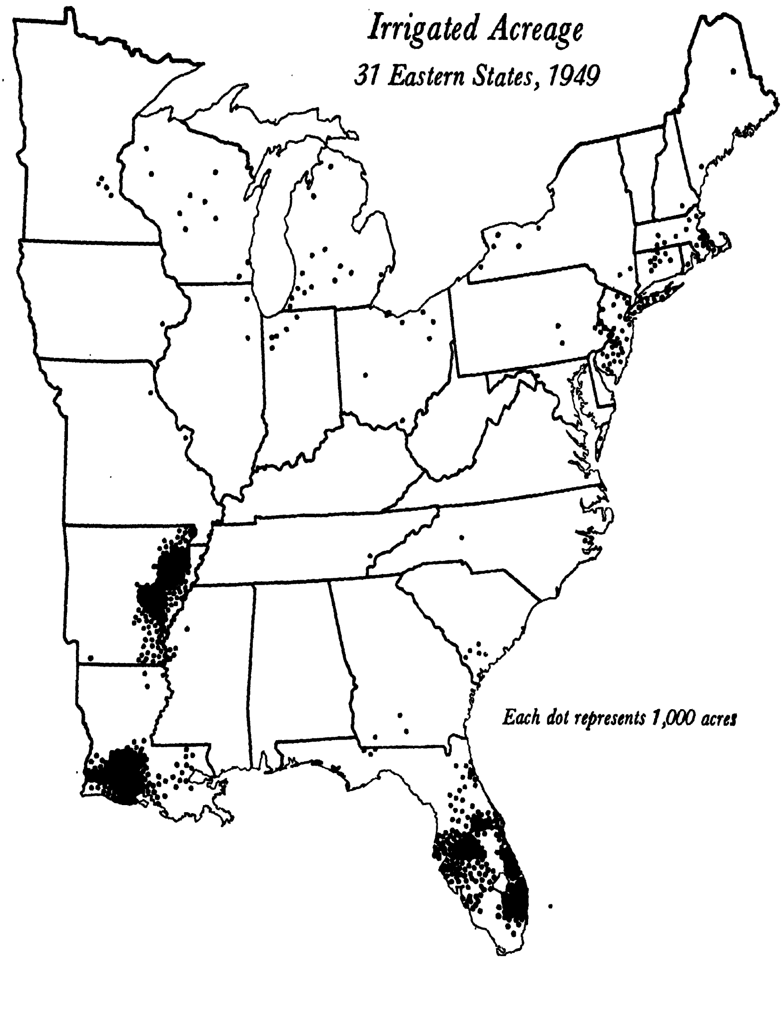
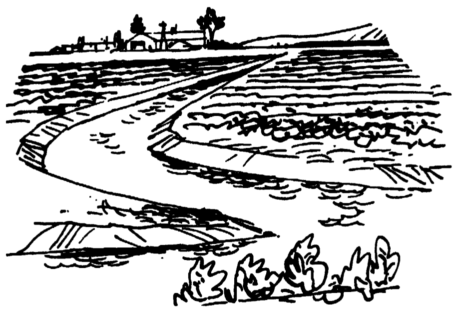


Water for Irrigation



The Expansion of Irrigation in the West

Elco L. Greenshields

The total area of irrigated land in the 17 Western States was about 27.5 million acres in 1953. That is only 3.5 percent of the total land in farms in those States, but its significance to agriculture is much greater than the figure indicates. About 12 percent of all cropland harvested was irrigated. More than 21 percent of all farms had some irrigated fields. The value of the crops harvested from irrigated land was about 35 percent of the value of all crops harvested.

Despite higher and higher costs of installing irrigation works and tighter limitations on the use of the available water, irrigation agriculture continues to expand. In the 10 years to 1950, 7 million acres were added to the irrigated land area of the 17 States. In each of the 5 years to 1950, an average of more than a million acres was brought under irrigation.

A great deal of new irrigation has been done since 1950, but the annual rate of increase appears to have been only about half the 1945–1950 rate. Expansion at the rate of a million acres a year could not be expected to continue indefinitely. During the Second World War, the Government and individuals had been kept from installing new irrigation facilities. With the release of material after the war, they were able to go ahead with their plans. High costs and lower prices for farm products caused some farmers to curtail the expansion of new irrigation. Another factor is that in most of the West easily developed water supplies are already utilized for irrigation. In places where water is still plentiful, topgrade land generally now can be reached only by costly pumping lifts or diversions.

Our estimate of irrigation acreage is based on sparse data for most States. Since the Census of 1950, which recorded 24,270,000 acres under irrigation in the West, the extent of irrigation has been surveyed only for a small part of the West.

That census, in April 1950, showed 1,138,000 acres irrigated in Utah in 1949. A sample census by the Bureau of the Census in October of 1953 in Utah indicated a total of 1,356,000, not including irrigated land not harvested and not pastured. About half of the increase, 90,000 acres, was irrigated pasture land.

The Nebraska State-Federal Division of Agriculture Statistics, which has made annual reports on irrigation in Nebraska, gave a total of 1,218,385 acres irrigated in 1953, an increase of more than 25 percent in 5 years. Land irrigated from wells gained 50 percent, to a total of 588,000 acres. By the end

of 1953, Nebraska farmers were pumping 9,718 wells for irrigation. An estimated 1,000 additional wells were drilled in 1954.

The rapid development of well irrigation in Nebraska has been possible because of the comparative abundance of relatively good ground water in generally shallow water-bearing materials, which are available to recharge from precipitation and streamflow. The danger of an overdevelopment in Nebraska appears to exist only in some small areas where recharge is restricted; the ground-water reservoirs are said to be large enough to hold reserves for the drier periods when depletion is likely to be greater than recharge. One factor in the expansion of well irrigation in Nebraska has been the use of gas engines for pumping. This cheap fuel has made deep-well irrigation practical for farmers.

An interagency committee survey of irrigation in the basins of the Arkansas, White, and Red Rivers in 1954 showed 1,648,000 acres under irrigation in Oklahoma and the parts of Colorado, Kansas, New Mexico, and Texas that are in those basins. That was 500,000 acres more than in 1949. The largest part of the increase was in the High Plains of Texas. Oklahoma in 1954 had 108,000 irrigated acres—more than twice the acreage in 1949. Irrigation in the Arkansas River Valley of Kansas has increased markedly.

The Texas Agricultural Experiment Station reported 4,680,000 acres irrigated in 1954—1.5 million more than in 1949. Since 1944, Texas farmlands put under irrigation have expanded by 3.3 million acres—a growth that put Texas close to California in total amount of irrigation. The 1950 Census reported 6.5 million acres irrigated in California. Irrigated acreage in California in 1945 totaled nearly 5 million acres, compared to 1.3 million acres in Texas.

More than half of the irrigated land in Texas is in the High Plains, where irrigation depends entirely on ground water, and annual rainfall varies from about 6 to 40 inches. More than half of the irrigation in the High Plains has been developed since 1950, but irrigation activity appears to have about reached a peak, and there has been some speculation as to whether ground-water supplies could support the 1955 level of development on a stable basis.

The lower Rio Grande Valley, the second largest general area of irrigation in Texas, has the most concentrated irrigation in that State. It is densely settled and intensively farmed. The climate is semitropical, and mainly vegetable crops and citrus fruits are irrigated. Of 718,000 acres equipped for irrigation, 680,000 acres were irrigated in 1954. Most of the water comes from the Rio Grande River. The low flow of the river in 1952 and 1953 led to a rapid expansion in the use of ground water. In 1951, 23,000 acres were irrigated by ground water. Some 160,000 acres were equipped for ground-water irrigation in 1954.

Some of the water from the lower Rio Grande is pumped twice or more before it reaches the fields. The completion in October 1953 of the Falcon Dam by the International Boundary and Water Commission was expected to make water supplies for the Lower Valley more dependable.

THE BUREAU OF RECLAMATION has contributed greatly to the development of irrigation in the West. In 1953, 69 Reclamation projects provided a full or partial supply of water to 7,147,000 acres. Between 1950 and 1954, Reclamation projects added 282,000 acres in new-land irrigation and provided supplemental water to an additional 995,000 acres, most of it in the Big Thompson project in Colorado. Projects under construction and authorized as of January 1, 1955 by the Congress included about 6.5 million acres of new irrigation in the West and provided for supplemental water for nearly 4 million acres.

Several programs of the Department of Agriculture have encouraged the

growth of irrigation. Through the water facilities loan program, administered by the Farmers Home Administration, credit assistance is given to individual farmers or groups of farmers in the Western States for a number of irrigation purposes. The basic law was amended in August 1954 to extend the use of water-facility loans to all States. Between 1949 and 1955, 4,002 initial water-facility loans were made for irrigation works on 6,585 farms. More than 450,000 acres will be irrigated by the facilities built through those initial and subsequent loans to the same borrowers. A total of 1,247 loans were made for drilling wells to irrigate 138,000 acres. Sixty loans were made for small dams to store water to irrigate 41,000 acres. Loans to construct canals and ditches to irrigate 83,000 acres were made to 210 borrowers. Two hundred borrowers obtained loans to purchase stream pumps to irrigate 15,000 acres. More than 1,000 loans were made to level 52,000 acres.

Through the agricultural conservation program of the Commodity Stabilization Service, aid has been given since 1941 for a number of irrigation practices, chiefly in the Western States. Farmers have used the help to construct nearly 14 million rods of ditches, dikes, and laterals, to build 11,400 dams to store or divert irrigation water, and to level more than 6 million acres of land. Other aids have included lining 675,000 rods of distribution ditches, building more than 400,000 drops, chutes, weirs, checks, and similar structures, and installing 3.5 million rods of flumes, siphons, pipelines, and culverts.

Another program of the Department, administered by the Soil Conservation Service, provides engineering and technical guidance to farmers for land and water conservation practices.

Farmers in the West sought this assistance in connection with more than 5 million acres of land leveling in 1949–53, and got technical guidance in applying water on more than 12 million acres.

No one measure of importance of irrigation in the total agricultural picture in the West can be devised. Half the land of the West is used for grazing. Only a small part of it is irrigated. Of the Nation's total nonforested pasture and rangeland, 85 percent, or more than 700 million acres, is in the Western States. Something like two-fifths of the cattle and calves and one-half of the sheep and lambs are produced on western ranches and farms. Irrigation has a part in this livestock output mostly through the production of feed grain and roughage.

Without irrigation, several million acres of western croplands would produce little or nothing. In appraising the value of irrigation, however, one has to consider that much western irrigable land could produce grazing for livestock or dry-farming crops without irrigation. The contribution of irrigation ranges from an increase in production of 100 percent on some lands down to an increase of 15 or 20 percent in the more humid sections. A reasonable overall estimate seems to be that irrigation means a 25- to 50-percent increase in yields over that obtainable without irrigation.

Irrigation also has increased hay and feed crops and so has made possible a larger and a more stable livestock industry.

Irrigation has brought a new agriculture to the valleys of the West—a greater variety of crops, many specialty crops, diversity in farming enterprises, longer seasons, a larger measure of stability.

The part of irrigation in western crop production would seem relatively larger if it were not for the vast wheat-producing capacity of the region under dry-farming methods. The 17 Western States account for three-fourths of the Nation's wheat output. Nearly four-fifths of the aggregate of four food grains—wheat, rice, rye, and buckwheat—are produced in the Western States.

Of the acreage of wheat in the West, ranging from 50 million to 62 million

acres in the 5 years to 1953, 2 million to 3.7 million acres have been irrigated. With the higher yields obtained, wheat produced with irrigation ranged from about 7 to 15 percent of the West's total production of wheat. Because wheat can be grown successfully by proper water conservation and dry-farming practices with annual rainfall as low as 12 to 15 inches, irrigation is unlikely to be extended greatly to wheat. Relatively higher potential gains through irrigation can be obtained on other crops.

Nearly all the rice, sugar beets, and citrus fruits in the West depend on irrigation. Two-fifths of the West's hay and forage production comes from irrigated land. Irrigation accounts for about one-tenth of the feed grains, two-fifths of the feed crops, a third of the cotton, and nearly four-fifths of all vegetables and fruits. While the crops that farmers irrigate shift from year to year in response to price fluctuations and other factors, the general tendency in recent years has been to irrigate the crops producing the highest values per acre.

About a fifth of the Nation's cotton in 1939 came from irrigated acres in the cotton-producing States of the West—Oklahoma, Texas, New Mexico, Arizona, and California. In 1954, the five States produced half our total cotton crop. One-third of the cotton of the West was grown by irrigation in 1949. By 1950, half of the cotton of the West came from irrigated land—by 1953, more than three-fifths.

The one-eighth of the Nation's crops that comes from irrigated land requires the use of only one-sixteenth of the Nation's harvested cropland. One acre of irrigated land thus has twice the capacity of nonirrigated land on the average. But in the Western States, 12 percent of the harvested cropland with irrigation produces 35 percent of the total crops other than pasture and forestry. Thus, in the West, an acre of irrigated cropland on the average approaches the equivalent of 3 acres of dry-farmed land.

The extent of irrigation in the West varies with the amount of rainfall and the type of farming. In the three Pacific Coast States, 70 percent of the crops, as measured by value, is grown under irrigation. In California about 85 percent of all crops is irrigated, in Oregon about 35 percent, and in Washington about 45 percent. In the eight Mountain States, about 60 percent of the total crop production is from irrigated land and in Arizona and Nevada nearly all crops are irrigated. In Utah and Wyoming, irrigation ranges between 75 and 85 percent of the total. In the North Dakota-Texas tier of States, about 5 percent of the crop production comes from irrigated land. In Texas roughly 15 percent of all crops comes from irrigated acres. In Nebraska better than 10 percent of crops are now produced under irrigation.

A CONTINUED EXPANSION of irrigation may be expected in the West, although at a slower rate than in 1945–1954. Much additional feasible development of surface water for irrigation will be carried out. Individual farmers will continue to expand the use of ground water for irrigation. Competition for unutilized water supplies, however, will grow keener and in general the cost of bringing in new land is likely to rise.

The surveys of the Arkansas-White-Red River Basins Inter-Agency Committee indicate an ultimate total potential of 3,040,000 acres for the part of the Basin that is in the Western States. The realization of this potential would put an additional 1,400,000 acres under irrigation. A need for providing supplemental water supplies to 525,000 acres irrigated in 1954 is also shown by the Committee report. The Committee pointed out that this indicated physical potential would require the maximum practicable utilization of available water supplies within the limits of available lands. Many possible projects are included that would not meet currently acceptable standards of economic feasibility.

The Bureau of Reclamation estimated that water supplies in the West were sufficient to irrigate a total of 42,243,000 crop acres. That would mean the irrigation of 6 out of every 100 acres of land in farms in the West. On the basis of this projection and my 1953 estimate of the extent of irrigation, there remains roughly 15 million acres of possible further development. The Bureau of Reclamation estimated that about 7.5 million irrigated acres do not get a full season's supply of water.

In the Missouri Basin, data available in June 1952 show a total area of 5.5 million acres developed for irrigation. An additional area of 6 million acres is physically susceptible of future development with a full water supply. The Missouri Basin Project is expected to bring in about 500,000 acres of new land and provide supplemental water to about the same acreage before 1962. In the Columbia River Basin, the area developed for irrigation is around 4,400,000 acres, and ultimate development could exceed 8 million acres. In the Central Valley of California, 5,600,000 acres are irrigated, with future prospects of an added 3,400,000 acres.

The Bureau of Reclamation in 1954 set forth a 7-year schedule of new development to supply a full water supply to 1 million acres and a supplemental supply to about 1.5 million acres. The fulfillment of the projected development would add 144,558 acres of new irrigation and supply additional needed water to 210,150 acres each year through 1960.

It should be pointed out that these Bureau of Reclamation projections of potentials are based primarily on physical—not economic—factors, principally on the factors of further conservation and storage of runoff. They consider that with present technical knowledge and facilities about a third of the water runoff can be put to use. Only about one-fifth of the average annual stream runoff of Western States is now being utilized. Further utilization of ground water for irrigation was not taken into account in the projections.

Present knowledge of supplies of ground water and recharge rates is insufficient for estimating the practical limits of well irrigation. Overexpansion of ground water may very well occur in many areas before the safe withdrawal rate is known. Overdraft by pumped irrigation wells may have occurred in some localities. Water-level measurements in observation wells in a six-county area of the High Plains of Texas show declines ranging up to 12 feet for 1 year, January 1953 to January 1954. Water authorities in the area say that the water table is dropping and that the economically recoverable water can be exhausted. But for the West as a whole, the full potential of underground water use has not been reached.

As greater reliance is placed on the use of the underground water storage, care must be taken to avoid depletion of these supplies beyond the average annual natural recharge. The possibility of the adoption of measures to speed up the recharge of underground water by various conservation practices should be explored thoroughly. Through research work now underway we may find practical means of adding water to underground reservoirs.

The future sound development of further irrigation in the West will require not only the harnessing of new water supplies but the better management of existing water supplies. The West will need to make more efficient use of its available water. Distribution losses in irrigation water supplies can and undoubtedly will be reduced.

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Supplemental Irrigation in Humid Regions

Max M. Tharp and C. W. Crickman

The humid area generally is considered to include the 31 Eastern and Southern States, which are bounded on the west by the tier of States from Minnesota southward to Louisiana. Annual rainfall varies from about 20 to 25 inches in northwestern Minnesota to 60 inches or more in some of the Gulf States. In most of the area, annual rainfall generally is enough to support sustained production of crops and pasture. Short periods of drought are common, however. Supplemental irrigation is used primarily to make up for poor distribution of rainfall during the growing season.

Supplemental irrigation is practiced in the East with a view to improving the kind of production already underway rather than to make possible a new kind of agriculture, as is typical in the West. Supplemental irrigation safeguards against droughts, increases yields, permits production of products of higher quality, provides earlier maturity, and maintains grazing capacities of pasture, especially in late summer and fall. Response from other improved practices, such as application of fertilizer, is also better with supplemental irrigation.

Sprinkler irrigation systems currently are used almost exclusively for supplemental irrigation in humid areas. Except for alluvial lands, soil and topography are such that flooding, surface ditches, and furrow irrigation usually are considered not feasible. Rice fields in Louisiana and Arkansas are flooded, some irrigation of vegetables in Florida and North Carolina is subsurface, and most of the irrigation of citrus fruits is by the furrow method.

Crops that require ground saturation or actual flooding, such as rice and cranberries, have long been irrigated in humid areas. The feasibility of irrigating other crops, such as vegetables and small fruits, has been recognized by eastern and southern growers for many years. But only in recent years have farmers generally come to realize the full potentialities of supplemental irrigation.

From 1939 to 1949, irrigated land in farms in the 31 humid States increased from about 739,000 acres to about 1,517,000 acres. In 1949, about 1 million acres of riceland were irrigated in Arkansas and Louisiana. Irrigated acreage outside the rice areas increased from fewer than 200,000 acres in 1939 to more than 500,000 acres in 1949.

The Census of Agriculture reported some irrigation in all the 31 States in 1949.

The largest irrigated acreage outside Arkansas and Louisiana was in Florida, where 365,000 acres were reported irrigated in 1949, primarily for growing vegetables, flowers, and citrus fruits. About 35 percent of the total value of all vegetables harvested for sale in Florida in 1949 were produced under irrigation and about 31 percent of the total acreage in orchards, vineyards, and nut trees. The area irrigated in Florida nearly tripled in the decade 1939 to 1949.

Other States in which substantial acreages were irrigated in 1949 included New Jersey, with 28,117 acres; New York, 19,248; Massachusetts, 18,507; and Michigan, 13,901.

About 6 percent of the total acreage of irrigated land in the United States in 1949 was in the 31 States—3.9 percent in Arkansas and Louisiana; 1.4 percent in Florida; and 0.7 percent in the other 28 States.

The number of irrigated farms in Arkansas and Louisiana increased from 8,566 in 1939 to 10,498 in 1949, or about 23 percent. Practically all of the increase was on farms that produce rice. In Florida, the increase in irrigated farms was from 3,947 to 6,075, or 54 percent. In the other 28 States the number of irrigated farms rose from 4,002 to 7,012, or 75 percent.

Sample surveys in several Eastern States indicate how fast supplemental irrigation has expanded.

A survey in Virginia in 1953 indicated that irrigated farmland increased from 2,817 acres in 1949 to 22,622 acres in 1953—about 700 percent in 4 years. The number of farms that reported irrigation rose from 71 in 1949 to 737 in 1953. Still, though, less than 0.2 percent of all farmland in Virginia was irrigated in 1953.

Data from surveys in Michigan indicated that the capacity of sprinkler irrigation systems in the State in 1953 was many times greater than the 14,000 acres reported by the census as irrigated in 1949. Similarly, a survey in New York in 1952 showed 1,570 farms with irrigated land totaling 45,800 acres—the census report for 1949 listed 888 irrigated farms, with 19,248 irrigated acres.

At the time the 1950 census was taken, supplemental irrigation was a minor practice in the Corn Belt and other Central States. The potentials for increasing yields in the area, however, indicate that irrigation may become more and more important. Research has shown that droughts lasting 10 days in the Corn Belt can substantially reduce corn yields, particularly if they come in the critical period of tasseling and silking. Pasture irrigation also shows promise in the Central States.

Among the factors that have encouraged supplemental irrigation in the humid areas are drought periods; improved irrigation equipment, particularly portable, lightweight pipe and sprinklers; better information on moisture requirements of crops and pastures; and relatively high farm incomes, which have favored investment in irrigation systems.

When prices received by farmers are high, irrigation has a better chance of providing a profit. Increased income derived from irrigation of a high-valued crop, such as vegetables, sometimes has enabled farmers to pay for irrigation equipment after 2 or 3 years of operation. With higher incomes farmers are more willing to use savings or to borrow money to make the substantial investments that irrigation systems require.

Although weather, soil, and the kinds of crops grown affect the need for irrigation, the feasibility of supplemental irrigation as a regular farming practice is conditioned by the availability of an adequate supply of good water for irrigation.

Variations in water requirements are illustrated by studies made by State agricultural colleges. As an example, Mississippi Circular 180 points out that 12 to 15 inches of irrigation water is required to keep perennial summer pasture productive throughout an average season. A study made in Kentucky indicated that an average of 6 acre-inches of water is required for each acre to be irrigated and that if reservoirs are used as a source of water supply provision should be made to store at least 2 acre-inches for each acre-inch used. The additional storage is needed to allow for evaporation, seepage, and other losses.

Serious shortages of water in growing seasons often occur in many sections of the humid areas. Only a few farms have streams, ponds, or wells sufficiently reliable to supply irrigation when it is most needed. This does not mean that the streams do not carry enough water during the year. It means that at the time of greatest supply, demand is usually at its lowest point. When supply is at its lowest point, or nonexistent, the demand for irrigation may be greatest. Seasonal shortages are among the major factors that affect the feasibility of supplemental irrigation.

Farm reservoirs, if they are large enough to meet peak irrigation needs and are properly located, offer a means of solving the problem of water supply. But to be a practical solution, the cost of the stored water in a farm reservoir, including costs of constructing the res-

ervoir, must be low enough to make it economically feasible for the farmer to use it for irrigation. The costs of building reservoirs depend on sites, capacity, height and length of fill, drainage area, and other factors. Before deciding to build a reservoir, a farmer should consider alternative sources of water.

THE USE OF sprinklers for supplemental irrigation has expanded rapidly in the humid States. In 1949, 2,084 farms in Florida reported the use of sprinklers and in the other 28 humid-area States (omitting Arkansas and Louisiana), 5,469 farmers had sprinkler irrigation. In Arkansas and Louisiana, where rice is irrigated by flooding, only 76 farms reported the use of sprinklers. In Florida, 34 percent of all irrigated farms reported by the 1950 Census used sprinklers. In 28 States, 78 percent were irrigated by sprinklers. Likewise, of all the farmland irrigated in 1949, 22 percent in Florida and 72 percent in the other 28 humid States was irrigated by sprinklers. The number of acres irrigated per farm by sprinklers in 1949 averaged 38 acres in Florida and 20 acres for the 28 other humid States.

High-value crops are usually the first to receive supplemental irrigation. Irrigation of pastures has been increasing, especially in the South. Vegetable crops, flowers, bulbs, citrus fruits, and shade tobacco are extensively irrigated in Florida. Vegetable and truck crops are also irrigated in the other Southern States and in the New England and Middle Atlantic States. Some farmers in Virginia and the Carolinas are irrigating bright leaf tobacco. Sprinklers are also used in Kentucky to a limited extent to irrigate burley tobacco. Supplemental irrigation is used in Midwestern States to produce vegetable and truck crops near large cities. Small acreages of specialty crops, such as sweet corn, strawberries, other small fruit, and nursery stock also are irrigated in many humid-area States.

Irrigation costs on farms vary with the number of acres irrigated, nearness of the water supply, pumping lift, kind and costs of power, type of system used, number of irrigations required, and other factors. Irrigation costs encompass annual charges for the investment that is required for equipment and the providing of water, costs of operation and maintenance, and costs of additional labor that may be associated with the use of supplemental irrigation.

In Wisconsin in 1951, the initial costs of installing sprinkler systems ranged from 75 to 100 dollars an acre when used for only one crop. The cost of applying an inch of water, including labor, power, overhead, and depreciation, ranged from 2.50 to 5 dollars.

In another study, conducted at the experiment station in Dixon Springs, Ill., the cost of irrigating 5 acres (at an irrigation rate of 2 inches per application or a total of 7 inches of water) in 1949 was 37.80 dollars an acre.

In Kentucky in 1951, 16 farmers made investments of 875 to 9,000 dollars for portable irrigation systems. The annual fixed costs for the systems ranged from 94 up to 856 dollars. The fixed costs per acre-inch varied from 25.82 dollars for a system that was used very little to only 66 cents for a system used at close to capacity. Labor was a primary factor in influencing the variable costs, which ranged from about 2 to 5 dollars per acre-inch of water applied. When 4.5 inches of water were used in three applications of 1.5 inch each on 20 to 25 acres with an investment of 3,000 dollars, fixed costs were about 2.75 dollars an acre-inch, and variable costs were about 3.25 dollars.

A 1953 report from Michigan indicated that the initial cost of providing a portable quick-coupling pipe sprinkler irrigation system varied from about 60 to 200 dollars an acre, depending on the size of the system and the number of acres irrigated.

Once an investment in an irrigation system is made, annual fixed and variable costs become the major concern to the operator. The amount of fixed costs depends on the size of investment

Labor Requirements and Costs per Acre of Irrigation Based on Use of Sprinkler System (Small to Medium Sprinklers) at State College, Miss.

[Each application 2 inches and no charge made for water]

Crop	*Equipment cost* [1] *per acre per year*	*Man-hours per acre*	*Labor cost* [2]	*Fuel*	*Total*
Corn:					
First irrigation	$12.50	4.5	$2.25	$1.60	$16.35
Second irrigation	....	6.5	3.25	1.60	4.85
Third irrigation	....	6.5	3.25	1.60	4.85
Total	12.50	17.5	8.75	4.80	26.05
Cotton:					
First irrigation	10.00	4.0	2.00	1.60	13.60
Second irrigation	....	4.5	2.25	1.60	3.85
Third irrigation	....	4.5	2.25	1.60	3.85
Total	10.00	13.0	6.50	4.80	21.30
Pasture:					
First irrigation	8.75	4.0	2.00	1.60	12.35
Second irrigation	....	4.0	2.00	1.60	3.60
Third irrigation	....	4.0	2.00	1.60	3.60
Fourth irrigation	....	4.0	2.00	1.60	3.60
Fifth irrigation	....	4.0	2.00	1.60	3.60
Total	8.75	20.0	10.00	8.00	26.75

[1] Equipment costs based on $100 per acre for corn, $80 per acre for cotton, and $70 per acre for pastures, 10-year life period and interest rate of 2.5 percent per year.
[2] Labor cost was 50 cents an hour.

Selection and Use of Irrigation Equipment for Mississippi, Circular 181, Mississippi Agricultural Experiment Station, State College, Miss., March 1953.

and the allowances made for interest and depreciation. The Michigan report suggested a 3-percent interest rate on the owned part of investment, with an average life of 10 to 15 years. An annual charge of 3 percent of investment was suggested for repairs, and another 1 percent of total value was allowed to cover property taxes and housing costs. The annual fixed costs were estimated to range from 14 to 17 percent of the initial investment cost.

Operating costs, of course, depend on the amount of use. Costs of power depend on size. Sources of power and labor requirements also vary according to many factors, including frequency and rate of application, spacing of laterals, type of equipment, and efficiency of the labor force. In Michigan it was estimated that labor requirements for supplemental irrigation would range from 1 to 1.75 hours per acre irrigated under average conditions.

Irrigation in the humid section generally is profitable in dry years, but little benefit may accrue from irrigation in some years. Yields may be increased for one year but not for another. There is need for data covering a series of years to test results in different climates. Applications of fertilizer and other management factors also affect the results obtained from supplemental irrigation.

The table overleaf shows some of the experimental results of irrigation in several States for various years. In interpreting the data, one must remember that 1953 was a very dry year and unusually favorable for irrigation in most of the States and that more favorable results are usually attained under experimental conditions than would likely be possible under farm conditions. The 1953 costs of irrigation are estimates, which were made on the assumption that overhead costs would average 16.50 dollars an acre and that

Additional Yield, Cost, and Net Income per Acre for Supplemental Irrigation

State	Year	Crop	Increase from irrigation: Unit	Increase from irrigation: Yield per acre [1]	Increase from irrigation: Price	Increase from irrigation: Value	Estimated cost of irrigation: Acre-inches water [1]	Estimated cost of irrigation: Cost per acre-inch [2]	Estimated cost of irrigation: Total per acre	Net increase in value per acre
Georgia	1953	Corn	Bu	64	$1.50	$96.00	7	$4.85	$34.00	$62.00
		Tomatoes	Ton	6	27.50	165.00	6	5.25	31.50	133.50
		Cotton:								
		Lint	Lb	295	.33	109.85	10	4.15	41.50	68.35
		Seed	Lb	502	.025					
		Sw. potatoes	Bu	140	3.15	441.00	10	4.15	41.50	399.50
		Gr. sorghum	Bu	22	1.40	30.80	3	7.83	23.50	7.30
Virginia	1953	Tobacco	Lb	......	......	316.00	7	4.85	34.00	282.00
		Corn	Bu	92	1.70	156.40	7	4.85	34.00	122.40
		Pasture, milk	Cwt	25.5	5.50	140.25	11	4.00	44.00	96.25
Missouri	1953	Corn	Bu	43	1.45	62.35	5.5	5.50	30.25	32.10
		Soybeans	Bu	14	2.50	35.00	4.7	6.00	28.20	6.80
		Cotton:								
		Lint	Lb	745	.33	277.57	7.5	4.70	35.25	242.32
		Seed	Lb	1,269	.025					
Tennessee	1953	Pasture, B. F	Lb	153	1.12	171.36	21	3.28	69.00	102.36
Massachusetts [3]	1949	Hay	Ton	1	29.00	29.00	6	4.83	29.00	....
Long Island, N. Y.[4]	1946	Potatoes	Bu	57	1.27	72.39	2.8	7.65	21.43	50.96
Pennsylvania [5]	1949	Potatoes, tobacco, apples, hay, and pasture.	....	......	......	......	4.6	13.40	61.64	....
Wisconsin [6]	1946	Potatoes	Bu	100	1.27	127.00	3.0	6.66	[7] 20.00	67.00

[1] 1953 data from annual report for 1954 of Soil and Water Conservation Research Branch, Agricultural Research Service, U. S. Department of Agriculture.

[2] 1953 costs estimated on basis of overhead costs of $16.50 per acre and operating costs of $2.50 per acre-inch of water. The estimated annual overhead costs assume use of equipment each year.

[3] New England Research News, February 1951. The New England Research Council on Marketing and Food supply.

[4] Potato Irrigation Costs and Practices in Suffolk County, N. Y., 1946, Cornell Agr. Expt. Sta. Bull. 862, 1950. The increase in yield per acre is for the period 1938–45.

[5] Irrigation on Pennsylvania Farms, Pa. Agr. Expt. Sta. Bull. 562, 1953.

[6] Irrigation in Wisconsin and Michigan, Economic Information for Wisconsin Farmers, October 1947.

[7] Farmers who irrigated had additional costs of $15 for fertilizer, $16 for seed, and $9 for spraying and other costs.

operating costs would average 2.50 dollars per acre-inch of water. The estimated annual overhead costs assume use of the equipment each year. To the extent that equipment was held in a standby status and not used each year, overhead costs would be higher, and the net increase in value would be less than the figures shown in the table.

The data in the table illustrate the wide range in yield response and net increase in value of different crops in various locations. For example, in the experiments in Georgia in 1953, the net increase in value per acre for grain sorghum was only 7.30 dollars, as against 399.50 dollars for sweetpotatoes. In Virginia, irrigation of pastures resulted in a net increase in value of 96.25 dollars an acre, but irrigation of tobacco resulted in an increase of 282.00 dollars an acre. The results are for only one year, and thus do not necessarily reflect the profitableness of irrigation over a period of years. Also, as we pointed out, the costs used in calculating the net increase in value were estimates. Therefore, under actual farm conditions, the values would likely be less favorable. The data are presented merely as indications of what might be expected from irrigation under the conditions stated or assumed.

Although cotton is generally recognized as a dry-weather crop, irrigation gave a good yield response in dry years in experiments carried on at Athens, Ga. The yield of seed cotton in 1952 was 742 pounds per acre on unirrigated land and 2,534 pounds on the irrigated plots. Rainfall in June, July, and August of 1952 amounted to 8.82 inches. In 1953, with rainfall in those 3 months totaling only 6.25 inches and with irrigations amounting to 9.91 inches (about the same as for the previous year), the yield of seed cotton was 934 pounds on unirrigated land.

A series of plot irrigation studies, begun in 1938 and covering 11 years, was conducted in Alabama to measure the effects of irrigation on truck and vegetable crops with and without use of other good agricultural practices. The basic treatments consisted of application of irrigation water, organic materials, and fertilizer at different rates.

The cumulative effects of applying intensive practices is illustrated by the results for Irish potatoes. Average yields for a 4-year period by treatment, as reported in Alabama Agricultural Experiment Station Bulletin 276, were as follows: No treatment, 28 bushels; 500 pounds of fertilizer (6–10–4) per acre, 80 bushels; 1,000 pounds of fertilizer, 115 bushels; 1,000 pounds of fertilizer per acre plus organic materials, 162 bushels; and 1,000 pounds of fertilizer, plus organic materials, plus irrigation, 229 bushels. The experiments illustrate the effect of using irrigation with other good practices.

Results of the experiments showed that irrigation gave marked increases in yields in some years and little or no increase in other years. Yields some years were less with irrigation than without. Response to irrigation was more closely related to distribution of rainfall than to the total amount of rainfall during the life of the crop. Irrigation improved the grade and quality and gave higher yields of marketable products.

Irrigation is becoming an integral

Response of Cotton to Irrigation, Athens, Ga.

Year	*Rainfall in June, July, and August*	*Irrigation*		*Seed cotton yields*	
				Unirrigated	*Irrigated*
	Inches	*Number*	*Inches*	*Pounds per acre*	*Pounds per acre*
1949	12.05	2	3.00	1,155	1,286
1950	9.93	1	1.50	1,087	1,430
1951	12.37	3	4.00	2,165	2,528
1952	8.82	7	9.44	742	2,534
1953	6.25	6	9.91	934	1,731

part of agriculture in the humid areas of the country. Experimental work and the experience of many farmers have proved that supplemental irrigation will produce additional yields of crops and pastures in most years in humid areas.

The economic question of whether the additional output will raise farm incomes enough to justify the higher costs is not so certain—benefits and costs vary greatly from farm to farm, and each farmer needs to appraise his own particular situation. But on an increasing number of farms the advantages are likely to outweigh the disadvantages. That means that irrigation in the East is likely to continue to expand—perhaps rapidly if farm prices are high but more slowly if prices are lower.

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Surface Irrigation Methods

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There are three general methods of applying irrigation water to the land. In surface irrigation the soil is the reservoir from which the plants draw the water they need. The soil also conveys and distributes the water over the field.

In sprinkler irrigation the water is conveyed above the field in pipes, and the soil acts as a storage reservoir.

In subirrigation the water flows underground, and the capillary water moves upward toward the surface of the land to meet the needs of the crops.

Surface irrigation, with which this chapter deals, includes the general methods of flood and furrow and corrugation irrigation.

In flood irrigation, the water is permitted to cover the surface of the land in a continuous sheet. Theoretically the water should be standing at every point in the fields just long enough for the soil to absorb the whole amount of water needed to refill the root zone. But under practical field conditions it is seldom possible to meet the theoretical requirement completely—some parts of the field usually receive too much water if all parts receive adequate water. If the size of the irrigation stream is properly balanced against the intake rate of the soil, the total depth of water to be stored in the root zone, and the area to be covered by the stream, however, the results will be reasonably uniform and efficient.

FLOOD IRRIGATION includes several methods: Border strip, basin, contour or bench border irrigation, flooding from contour ditches, wild flooding, and border ditch.

The object of border strip irrigation is to advance a sheet of water down a narrow strip between low ridges or borders and to get the water into the soil as the sheet advances. The strip must be well leveled between the border ridges and the grade down the strip must be fairly uniform to avoid ponding. The ridges should be low and rounded so they can be planted with the strips and no land lost to production.

Border strip irrigation is well adapted for all close-growing crops and is used for some row crops, such as cotton. Hay and grain can be irrigated on uniform slopes up to 3 percent. Established pasture can be irrigated on uniform slopes up to 6 percent. The method can be used on soils of coarse or fine texture. It utilizes large water streams safely. Its requirements as to labor and time are low. It provides for

uniform wetting and efficient use of water.

Basin irrigation is adapted especially to flat lands. It consists of quickly filling a diked area with water to the desired depth and allowing the water to percolate into the soil. It is desirable for close-growing crops and orchards on medium- to coarse-textured soils and for rice that is grown on fine-textured, slowly permeable soils. When the basins are properly graded and built to the right dimensions for the kind of soil and water supply, water can be applied efficiently and alkali can be controlled.

Contour, or bench border, irrigation is adapted to fairly uniform, moderate slopes with deep soils. Border strips are laid out across the slope on a controlled grade, and the ridges are constructed parallel to each other. If the strips are laid out on a grade, they operate about the same as does border strip irrigation. If the strips are short and level, it is like basin irrigation.

Flooding from contour ditches is used often on close-growing crops on sloping or rolling lands not subject to the degree of leveling necessary for other methods of irrigation. Water is flooded downslope between closely spaced field ditches running along the contour of the land. The ditches prevent the water from concentrating and causing erosion. Fairly uniform wetting is possible, but labor costs of irrigating are rather high. In general, this method should not be used if a more desirable method can be used.

In wild flooding, the stream of water is diverted from its course and allowed to spread out over the field at random. It is not recommended, because the low spots in the field will get too much water and the high spots will receive none.

The border ditch method is used in some of the older irrigated areas of the West, but it is not generally recommended. Parallel ditches 25 to 200 feet apart are run down the field in the direction of the land slope. The strips of land between the ditches are irrigated by diverting the water at intervals from either side of the ditch. The method uses water and labor inefficiently. The ditches often erode on the steeper slopes and silt full on the flatter slopes. They take a considerable area of land out of crop production and act as a weed nursery for the rest of the field.

Furrow irrigation is the most common method of applying water to row crops. Water is applied in the furrows between the rows of plants. As water runs down the row, part of it is being absorbed all along the furrow and is moving through the soil to refill the moisture-storage reservoir of the soil under the growing plants. It is adapted to all row crops, truck crops, orchards, vineyards, and berry patches on gentle slopes on all but the coarser soils.

Cultivation of the furrows to control weeds keeps the soil loose. When the furrows run down the slope, serious erosion can occur unless the size of the irrigating stream is carefully controlled.

Furrow irrigation is usually expensive from a time and labor standpoint. Properly operated, it is fairly efficient in its use of water.

Contour furrow irrigation is an adaptation of furrow irrigation, in which the furrows are laid across the slope on a carefully selected grade. A reduction in the grade of the furrows makes them much less subject to erosion by irrigation water and rain.

Corrugation irrigation is well adapted to close-growing crops on sloping and rolling lands and to soil slow to take water. The water is applied in small furrows running down the slope from the head ditch. The purpose of the furrows is not so much to carry the stream of water as to guide it. Some overtopping of the furrow may occur. Corrugation irrigation is suitable for fine-textured soils that take the water slowly and tend to seal over and bake when flooded. It provides uniform wetting and prevents erosive

water accumulation on land too rolling or steep for borders or basins and makes use of small irrigating streams. It is relatively expensive in labor.

A FARM DISTRIBUTION system is necessary to convey the irrigation water to the various fields from the point at which the water is available on the farm.

The system must be designed to carry enough water to meet the demands of the crop to each field without erosion and allow for efficient application. It must be laid out in accordance with good farm management practices. It must provide for conveying and regulating the irrigation stream and for the roads and drains that are needed. It must be located to give minimum interference with seeding, tillage, and harvesting.

OPEN DITCHES are the most common means of conveying irrigation water. In many areas the ditches to each field are permanently constructed and maintained. They form field boundaries and have permanent conveyance and control structures. Often their banks are seeded to perennial grasses to control weeds and provide extra stability. They usually have flat bottoms. Side slopes may be in the ratio of 1.5 to 1 or flatter, and are designed to carry the stream at a nonerosive velocity. Permissible velocities may be as high as 6 feet a second on shales and hardpans and as low as 1.5 feet a second in fine sands.

In areas where the seasonal requirements are low and only one or two irrigations are required, it is often wise to utilize temporary ditches for distributing the water to the fields. Such ditches are built with farm-type ditchers; they may have flat or rounded bottoms or a V cross section.

In medium- and fine-textured soils, side slopes are sometimes quite steep to reduce the overall width of the ditch and to facilitate the installation of temporary checks or other structures. These ditches are plowed in after the irrigation season is completed as a measure of weed control and to remove obstructions to harvesting operations.

Temporary ditches also are used for conveying the water from the edge of the field to the individual furrow or border. They are usually installed after the crop is planted, are used during the irrigation season, and are removed before harvest.

CONVEYANCE STRUCTURES of various types are usually necessary in open ditches to deliver water at the desired elevation on each field. Often an intervening low area between the water source and the upper part of the field requires the use of flumes or inverted siphons to carry the water across the draw or swale. These permanent structures should be well designed and constructed to fulfill their purpose and eliminate excessive maintenance.

When any minor depressions are encountered, a compacted earth fill is often placed and the ditch constructed on its top. Drainage water can be carried from one side of the embankment to the other by a culvert placed below the bottom of the irrigation ditch. Such installations, while relatively cheap to construct, pose problems of maintenance and are subject to damage from rodents and burrowing animals.

When ditches are constructed across porous soils, the loss of irrigation water by seepage may be serious. If so, permanent ditches may be lined with such less permeable material as clays or bentonites. The ditches may be lined with concrete or asphaltic concrete or may be sealed by means of a thin flexible membrane. Membrane linings are usually buried a few inches below the ditch surface to protect them from mechanical damage.

Important parts of any farm distribution system are the crossing structures, which permit the movement of machinery, produce, and livestock across the irrigation stream. Often they can be made a part of other structures. Sometimes culverts or bridges are provided.

CONTROL STRUCTURES placed in open ditches may be of many types. Their function is to measure the flow, provide a means of diverting the water from the ditch, or to lower safely the water from one elevation to another.

To make proper application of the water, the irrigator should know the size of the stream he is using. Measuring devices should be part of the distribution system and should permit the farmer to determine the flow being delivered to any point on his farm. Parshall flumes or weirs are often used for the purpose. Other structures in the system are sometimes calibrated so that reliable estimates of the flow may be made.

Water-control structures may be classified as division boxes, turnouts, and checks. Division boxes are used if the stream is divided into two or more sublaterals and may or may not be equipped with gates to control the flow. Turnouts provide a means of delivering water from the ditch to the area to be irrigated or into a temporary ditch. Checks are adjustable dams placed in the irrigation ditch to provide a means of controlling the depth of water serving the turnouts. Often it is advantageous to install structures that perform two or more of the functions.

Permanent ditches usually are equipped with permanent or semipermanent structures of concrete, masonry, timber, or metal. Temporary ditches usually have portable structures, which may be quickly installed or moved as needed.

Siphon tubes or spiles often are used to deliver the water from temporary ditches. The tubes, which carry water over the ditch bank by siphonic action, are made of a variety of materials in a number of sizes. Small tubes may deliver as little as a gallon a minute. The larger ones carry as much as 2 cubic feet a second. Spiles, or tubes laid through the ditch bank, also are commercially available for a similar range of flows.

A temporary check dam of a common type is made from a sheet of flexible plastic or canvas attached to a supporting rod or beam. The dam is placed across the ditch in such a way that the rod or beam rests on the ditch banks and the plastic or canvas material is tucked into the ditch side and bottom upstream. Such devices usually can be adjusted so that some of the flow may be carried downstream through a sleeve or over the top of the dam. Other types of temporary checks are made of sheet metal, pipe, fabric, or combinations of those materials.

Open ditches must carry the required flow of water without scouring. Erosion-control structures often are necessary to reduce the grade in the earth sections of the ditch. The structures have many forms and materials. A common type is a weir notch, equipped with an apron at a lower elevation so that the water may be dropped vertically to reduce the velocity of the water in the earth ditch to a safe value. Others consist of paved ditch sections on steep grades—often called chutes—or buried pipes, which will lower the water. Regardless of the type, the structure must be able to carry the required flow and provide for dissipation of the energy in the falling water before it enters the earth ditch section below.

Pipelines are usually more expensive to install but have advantages over open-ditches. Pipelines may be used to convey water by gravity alone or under pressure across a swale or to a higher elevation. They are essential when pressure is necessary to operate the system.

Permanent pipelines usually are buried and are equipped with necessary hydrants, relief stands, and other devices to control the water and protect the line. Permanent lines are commonly made of concrete, clay, asbestos-cement, or steel pipe. Plastic and aluminum pipe have become popular.

Portable surface pipes or hoses provide a good method of conveying the water to the field or to the individual border, basin, or furrow. They are

made of light materials—steel, aluminum, plastic, or canvas—and often are equipped with patented coupling devices for ease in connecting. They may be manufactured with small, adjustable gates, which permit the release of a small stream into each individual furrow.

Pipelines must be carefully planned to meet the requirements of the crop, fit the site conditions, and provide for economy of installation and operation. Because they eliminate losses from seepage and evaporation and provide excellent control of the water, they have found favor in many areas where water is scarce or expensive.

THE LAYOUT AND MANAGEMENT of the system needs careful planning as to soils and topography, intake rates and water-holding capacities of the soils, the amount of water that can be run in each furrow or border strip without causing erosion, and the relationship between length of run and size of irrigation stream to get the proper amount and distribution of moisture in the root zone.

Excessive irrigation wastes not only water. It also causes the leaching of water-soluble nutrients beyond the reach of the plants. Too heavy irrigation on higher land often causes waterlogging of rich, lower lands. Usually such a situation can be corrected only by a costly system of drains and reclamation.

How to apply irrigation water to crops without causing soil to erode is a big problem. Improvement in the fertility and structure of soil usually helps it absorb water faster. As the rate of intake increases, larger streams of water must be delivered to the furrows and borders to get uniform irrigation. Even though erodibility may be reduced by good soil management, the effect of the larger streams more than offsets any such gain. Thus the soil characteristics that influence irrigation methods are not stable. Conditions change from year to year with the cropping practices and even from irrigation to irrigation in a single season.

Theoretically it would be desirable to change the irrigation layout of a field at each successive irrigation for maximum efficiency. From a practical standpoint, continuously changing the length of run and spacing of furrows is not possible. Therefore the irrigation engineer, taking into account all of the influencing factors and the magnitude of change that might take place throughout the season and the rotation period, must choose practices that will be safe and reasonable for the conditions of the site.

Some suggestions are given for the layout and stream size generally most desirable.

FURROW AND CORRUGATION LAYOUTS are handled together because they are both subject to erosive action and both are thought of as generally carrying the water from one end of the field to the other.

The allowable size of streams on sloping lands largely depends on the slope at which the furrows are laid out. The general relationship of maximum allowable furrow stream and slope is $Q=\frac{10}{S}$, in which Q is the maximum nonerosive furrow stream in gallons per minute and S is the slope of furrow in percentage.

Thus, if the slope of the furrow is 0.2 percent, the furrow will carry 50 gallons a minute without serious erosion. With a slope of 2 percent, the furrow will safely carry only 5 gallons a minute.

With the flatter slopes, erosion probably will not be a factor—the carrying capacity of the furrow limits the size of stream that can be carried.

Maximum allowable length of run depends on several factors, including the maximum allowable stream size, the rate at which water is absorbed by the soil, and the amount of water to be stored each irrigation. The last two factors particularly vary throughout the season. The accompanying tabulation gives the values suggested for average conditions.

Spacing of furrows and corrugations sometimes can be varied within certain limits. Spacing greater than 30 inches generally is not desirable for most annual crops, because the root zone is so limited during much of the season. Of course many row crops are grown at a greater spacing and the furrow spacings are fixed.

In general, the coarser the soil, the closer the corrugations should be spaced for efficient irrigation, but spacings of less than 15 inches are seldom practical to construct and maintain.

Flow control from the field lateral to the individual furrows and corrugations is usually by siphons, spiles, or open cuts in the bank. For efficient and safe irrigation, however, positive controls are needed. Furrow streams of varying size do not give uniform application of water, and the larger streams may cause excessive erosion.

Border strip layout depends on the intake rate of the soil, the slope, and the depth of application.

The size of the border strip should not be greater than the maximum allowable or available stream will cover uniformly during the irrigation set, without excessive losses. The width is largely governed by the slope of the land and the amount of water that can be safely carried through turnouts to the strip. The length is limited by the size of stream per unit of width of strip that will flow without causing erosion.

For example, with slopes of 0.5 percent, a flow of 0.1 cubic foot per second per foot of border strip width may be safely used; with a slope of 2.0 percent, the safe value falls to about 0.035. Thus a longer run (length of border strip) is possible on the flatter slopes.

The height and shape of the border dikes are important. A common error is to build the dike too low to control the flow. The dikes must be higher for the flatter slopes than for the steeper ones. The base of the dike also should

usually be broad, so that farming operations can be carried on over the dike. Seldom should the sides of the dike be steeper than 2 horizontal to 1 vertical. Thus, on the steeper land where a minimum height of dike is 3 inches, the base would need to be at least 18 inches wide. On flatter lands where a 6-inch-high dike is needed, the minimum base width of the dike should be about 36 inches.

Properly constructed dikes allow for crop growth right over the dike and still control the flow of water during irrigation.

The size of the irrigation stream depends on the soil, size of border strip, and depth of application. Soils of high intake rates require large streams to get the water over the land rapidly if excessive deep-percolation losses are to be avoided. Likewise for shallow irrigations large streams must be used. Small streams are desirable for deep applications.

The table on the next page suggests the relationship between size of stream needed to irrigate border strips of various sizes under different site conditions:

Control of flow into the border strips can be by open cuts in the bank of the field lateral, through open or pipe turnouts, or through siphons over the bank. In loose, sandy soils and in places where large flows are desirable, siphons that will carry up to 2.0 cubic feet a second each have been found useful. Such siphons require the use of

Border Irrigation Relationships for Various Soils, Slopes, and Depths of Application

Soil texture	Slope of land	Depth of application	Suggested border-strip size		Size of irrigation stream
			Width	Length	
	Percent	Inches	feet	feet	Cubic feet per second
Coarse	0.25	2	50	500	8.0
		4	50	800	7.0
		6	50	1,320	6.0
	1.00	2	40	300	2.75
		4	40	500	2.50
		6	40	900	2.50
	2.00	2	30	200	1.25
		4	30	300	1.00
		6	30	600	1.00
Medium	0.25	2	50	800	7.0
		4	50	1,320	6.0
		6	50	1,320	3.5
	1.00	2	40	500	2.5
		4	40	1,000	2.5
		6	40	1,320	2.5
	2.00	2	30	300	1.0
		4	30	600	1.0
		6	30	1,000	1.0
Fine	0.25	2	50	1,320	4.0
		4	50	1,320	2.5
		6	50	1,320	1.5
	1.00	2	40	1,320	2.5
		4	40	1,320	1.25
		6	40	1,320	0.75
	2.00	2	30	660	1.0
		4	30	1,320	1.0
		6	30	1,320	0.67

a priming pump, but are relatively easy to handle and positive in action. The investment in an adequate number of siphons to irrigate a large field is relatively small, compared to the cost of adequate permanent turnouts. The use of siphons lets the head ditch remain open, so that it can be cleaned by machines instead of hand labor.

Basin irrigation depends on using relatively small, level areas surrounded with dikes high enough to store the desired depth of water on the land. The irrigation stream is large enough to fill the basin quickly and then be turned into the next.

The basin dikes are often higher and steeper than those used with border irrigation, as it is not so common to farm over basin dikes.

Stream sizes desirable for basin irrigation should be considerably larger per unit of land area than with border irrigation. Possibly a good guide for the proper stream size would be to use at least twice as large a stream per unit of area as was suggested for the flatter grades with border irrigation.

Stream control to the basins is usually through some type of open or pipe turnout that has adequate capacity for the large streams required.

Flooding from contour ditches is common practice on some of the

Furrow Irrigation Relationships for Various Soils, Slopes, and Depths of Application

Soil texture		Coarse				Medium				Fine			
		Depth of irrigation application, inches											
Furrow slope	*Maximum allowable nonerosive furrow stream*	2	4	6	8	2	4	6	8	2	4	6	8
Percent	*Gallons per minute*	*Maximum allowable length of run, feet*											
0.25	40	500	720	875	1,	820	1,	450	650	1,050	1,500	1, 50	2,140
0.50	20	345	480	600		560		975	120	730	1,020	1, 50	1,460
0.75	13	270	380	480	550	450	630	775	900	580	820	1, 00	1,150
1.00	10	235	330	400	470	380	540	650	760	500	750	850	990
1.50	7	190	265	330	375	310	430	530	620	400	570	700	800
2.00	5	160	225	275	320	260	370	450	530	345	480	600	675
3.00	3	125	180	220	250	210	295	360	420	270	385	470	550
5.00	2	95	135	165	190	160	225	270	320	210	290	350	410

older irrigated lands of the West, where the topography is rather rough. The contour ditches should be set with practically no grade if they are not too long. For longer ditches, a slope of 0.1 foot per 100 feet is usually adequate and is easier to handle.

Spacing between contour ditches should not be too great. With fine-textured soils on grades of 1 to 2 percent, the spacing should not exceed 250 feet. On the same grades, ditch spacing on the coarser soils should not exceed 100 feet. For 5-percent slopes, the distances should be 150 feet and 50 feet, respectively.

The size of stream required at any one turnout along the contour ditch need not be large, because the area of land such a stream is expected to cover will be small. The stream sizes, per unit of area, suggested under border irrigation generally apply to the contour ditches.

Flow control from contour ditches is often by cuts in the ditch banks, particularly if the banks are sodded. Siphons have been satisfactory in some localities.

Specifications for surface irrigation methods cannot be entirely rigid.

Many of the factors affecting the relationships of length of run, the size of stream, and spacing of corrugations vary widely throughout the irrigation season and throughout the crop rotation period. The foregoing specifications, however, will satisfy average conditions when good farming is practiced.

BORDER STRIP irrigation generally will not function properly when the slope in the direction of flow is more than 2 percent. Pasturelands sometimes utilize borders on steeper grades up to about 6 percent, but the distance between border ridges must be reduced to about 10 to 15 feet. The steepest downfield slope on any one border strip should not be greater than twice the flattest, and the grade should either increase or decrease consistently from one end to the other without undula-

tion. A cross slope as much as one-tenth of a foot is allowable within an individual border strip; that often provides the limiting factor for the width of border strips. For example, a field with a cross slope of 0.2 percent could not have border ridges more than 50 feet apart.

Corrugations can be successfully used on slopes as high as 8 percent in places where runoff from rains is not a serious problem and where the irrigation water is carefully controlled. The slope of the corrugation within the run should not undulate. When the grade increases down the field, the steepest portion should not have a slope greater than twice the flattest, and the total change should not exceed 2 percent. When the grade decreases, the steepest part should not be more than one and one-half times the flattest, or a total change of 1 percent. If the grade of the corrugation is more than 2 percent, a cross slope as high as 0.5 percent may be permitted, but on flat grades the cross slope should not be greater than one-fourth the down-field grade.

Furrows, like border strips and corrugations, should not have an undulating profile. They may be used on slopes up to 3 percent when erosion from rain is not a problem. The steepest grade in the profile on increasing slopes should not be greater than twice the flattest; on decreasing slopes, the steepest should be less than one and one-half times the flattest.

The maximum allowable cross slope depends on the depth of the furrow. When furrows are about 9 inches deep, cross slopes up to 8 percent are satisfactory on fine- and medium-textured soils. On coarse-textured soils, the upper limit of cross slope is 5 percent; on very coarse soils it is 2 percent. With medium-depth furrows, 6 inches, the allowable cross slopes are 3 percent, 2 percent, and 1 percent, respectively, for fine or medium, coarse, and very coarse soils. Shallow furrows, 3 inches, may have cross slopes of 0.5 percent on medium and fine soils and 0.3 percent on coarse soils. These requirements are very important when the contour irrigation is the method to be used.

Basins or level borders require grades less than 0.1 percent with no cross slope. If contour levees are used, such as in rice basins, the land slope should not exceed 1 percent, and the levees should be spaced so that the vertical interval between dikes is not more than 3 inches.

Surface irrigation should be supplemented with a complete water-disposal system to remove waste waters and to eliminate unwanted ponding. The drains should be designed to carry off short, peak flood flows as well as irrigation waste water. Provisions are needed to allow basins or levee systems to be drained when desired. Drains often need some protection—vegetation or some structure, to carry the water without erosion. Drains should be equipped with crossings so that farm equipment can be moved over them.

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The Use of Sprinklers for Irrigation

Tyler H. Quackenbush and Dell G. Shockley

American farmers first used sprinkler irrigation in 1900 or so. In 1955 more than 2 million acres were irrigated with sprinklers.

Lightweight aluminum pipe with quick couplers came into widespread use after 1945. It cut labor costs of the earlier portable systems and demonstrated that sprinkler irrigation could be adapted to most sites and crops in the United States.

The advantages of sprinkler irrigation, properly installed and operated, are:

Erosion can be controlled. Safe irrigation is possible on land too steep for the efficient use of other methods. If soil erosion is a hazard, sprinkler irrigation is well adapted for use in conjunction with mulching, terracing, and stripcropping.

Uniform application is possible on all kinds of soil. On sandy soils that have high intake rates, sprinkler irrigation distributes water better than other methods do. Water can be saved, more land can be irrigated, and drainage problems may be reduced.

The amount of water can be controlled to meet the needs of the crop. Light applications of water can be made to seedings or young plants.

Land preparation is not required. Soils too shallow to be leveled properly for other methods can be irrigated safely with sprinklers. On deeper soils the costs of land leveling can be eliminated or greatly reduced.

More land is available for cropping. Field ditches, corrugations, and dikes are not needed. It also lessens the weed problem, reduces wear on farm machinery, and simplifies tillage. Surface runoff of irrigation water can be eliminated.

Small streams of irrigation water can be used efficiently. Many small farms that have a continuous-flow water supply often have insufficient water to irrigate efficiently with surface methods.

The time and amount of application of fertilizers can be controlled to meet the needs of the plants. Water-soluble fertilizers can be applied through the sprinklers.

Labor costs are reduced, notably on soils having high rates of intake and on land that is steep or rolling. Irrigation can be fitted into other farming operations as incidental work that is done once or twice a day.

Crop damage from frosts can be reduced by the use of specially designed sprinkler systems.

The limitations are:

Wind may distort sprinkler patterns and cause an uneven distribution of water. When the spray is blown about, parts of the field may get too much water and others too little.

A constant water supply is needed for the most economical use of the equipment. The water must be clean and free of sand and debris.

The first investment is high. The equipment must be handled carefully.

The power requirements are high. As sprinklers operate with water pressures of 15 to more than 100 pounds to the square inch, extra power usually is needed.

Tight soils, which have slow intake rates, cannot be irrigated efficiently in hot, windy climates. When water is applied at the low rates required for such soils, the percentage of loss by evaporation and wind drift is increased greatly. Costs of labor or installation may be higher on fields that remain muddy for some time after irrigation has been completed.

Two types of sprinkler systems are used to irrigate farm crops. One uses sprinkler heads. The other uses perforated pipe.

Sprinkler-head systems are the more widely used type. They may be designed as permanent installations, with buried main and lateral lines. They may be semipermanent, with fixed main lines and portable laterals. Or

they may be set up as fully portable systems. In all, water is delivered through a main line from the source of supply to the lateral lines. It is discharged into the air through nozzles on the sprinkler heads, which are mounted on riser pipes attached to the laterals.

Each sprinkler head applies water to a circular area. The diameter of the circle is governed by the nozzle size and the water pressure. The water is not applied evenly over the entire wetted area, so sprinkler heads usually are spaced to provide an overlap. For uniform coverage, the distance between sprinkler heads on a lateral should be between one-fourth and one-half the diameter of the wetted circle. The spacing between laterals, or the distance portable laterals are moved, can be greater, but moves of laterals should not exceed 0.7 the diameter of the wetted circle.

Sprinkler heads are of several kinds. Some rotate, and some are stationary. Some have two nozzles and some have one. The two-nozzle, revolving-head type is used most commonly. One of

Double-nozzle, revolving-head sprinklers spaced 40 feet apart on a portable "quick-coupled" aluminum lateral line.

the nozzles, called a range nozzle, is set to throw water to the outer part of the wetted circle. The other nozzle, called a spreader nozzle, is smaller. It applies water to the area close to the sprinkler head. The jet from the range nozzle activates a device that causes the sprinkler head to turn at a rate of about three revolutions a minute. Such sprinklers can be used to apply water at average rates of 0.2 inch to more than 1.0 inch an hour.

Single-nozzle, revolving-head sprinklers are similar to the double-nozzle type with the spreader nozzle plugged. Generally, though, they are made with smaller nozzles and should be spaced closer together along the lateral lines. Usually they have a lower nozzle angle and a flatter trajectory. Some are designed to replace double-nozzle heads in windy places and wet areas of about the same diameters as the double-nozzle type. The smaller single-nozzle heads are adapted for orchard irrigation, but seldom are used for field crops.

The stationary, or fixed-head, sprinklers are adapted for use in low-growing, close-spaced orchards, such as citrus groves. They apply water to small areas at low average rates. Some are designed so the diameter of the wetted circle can be varied. Usually they are set between tree rows, and no attempt is made to obtain overlapping wetted patterns.

Sprinklers with perforated pipes deliver water through very small holes, drilled at close intervals along a segment of the circumference of a pipe. Usually there are several rows of holes, so the trajectories of the jets provide fairly uniform distribution of water over a strip of land along both sides of the pipe. Some systems have one row of holes, and the water is distributed by rolling, or oscillating, the pipe through an arc of about 180° with a water-powered motor. Because oscillating-pipe sprinklers must be supported above the ground, their most common use is for permanent installations in small nurseries and vegetable plots.

The width of strip irrigated from a perforated pipe depends on the size of the holes and the water pressure. Usual designs provide for coverage of a strip about 40 feet wide and an operating pressure of about 25 pounds to the square inch. After one strip has been irrigated, the pipe is uncoupled and moved 40 feet to irrigate the next strip. Water is delivered to the lateral through a buried or a portable main.

Perforated-pipe sprinklers are adap-

ted for use on soils of relatively high intake ability. They are satisfactory when soils will absorb water as fast as an inch an hour. They are apt to cause puddling or erosion, however, on tight soils that absorb water slowly. Because oscillating-pipe sprinklers have only one row of holes, they apply water slowly and may safely be used on nearly all types of soil.

THE PARTS of all sprinkler systems are similar in most respects. They consist of the pump to provide the needed pressure, the main pipelines and laterals, and the sprinklers.

Turbine or horizontal centrifugal pumps are best. The turbine type is used to pump from relatively deep sources of ground water. Centrifugal pumps are used with surface water or shallow wells; generally they are cheaper to install and operate, but they can be used only where suction lifts are less than about 15 feet. Turbines generally should be set at fixed locations, but centrifugal pumps may be portable or in permanent installations. Both types must be designed to lift the required amount of water from the source of supply to the highest point in the field and maintain an adequate operating pressure.

Electric motors and internal-combustion engines are used to drive the pumps. Electric motors are better for fixed installations if adequate power is available. Otherwise gasoline, diesel, or natural-gas engines can be used. Gasoline and diesel engines are also adapted for use with portable pumping units. All types of power units should be equipped with automatic cutoff devices that will shut off the power if the main line pressure drops below a fixed level for any reason. Internal-combustion engines also should have a safety cutoff that is controlled by the oil line pressure.

Main lines may be permanent or portable. Permanent mains are used to best advantage on farms where field boundaries are fixed and where crops require full-season irrigation. Portable mains are more economical when a sprinkler system is to be used on any of a number of fields. Steel pipe is used for most permanent main lines. Asbestos-cement and iron pipe also are used, but concrete-pipe lines are not adapted for use in high-pressure sprinkler systems. The permanent lines should be buried so as to be out of the way of farming operations. Lightweight aluminum pipes with quick couplers are used for most portable main lines.

The lateral lines usually are portable. Buried permanent laterals are used for some orchards, tree nurseries, and for other special sites, however. Quick-coupled aluminum pipe is best for most portable laterals. Laterals should be connected to valved outlets on the main line. The outlets generally are installed at the designed lateral spacing, but in some instances one outlet is designed to serve several lateral positions. Extra lengths of pipe will be needed in such cases to convey the water from the outlet to the offset lateral position.

Sprinklers used to distribute water over the field surface differ in design. Revolving-head sprinklers are made for use with pressures from as little as 15 pounds to more than 100 pounds to the square inch. It is important that the proper pressure be provided for the sprinkler heads to be used. Pressures too low or too high for a particular sprinkler head will cause poor water-distribution patterns. Pressure requirements for perforated-pipe sprinklers are less critical. The width of strip irrigated from a perforated pipe will vary with the pressure used, however, and lateral spacing will need to be adjusted to this width to provide satisfactory coverage.

DEBRIS SCREENS usually are needed when surface water is used. Details vary, but the function of such screens is to keep the system free of trash that might plug the sprinkler nozzles. Screens should be fine enough to catch weed seeds and other small particles. They also may be required to prevent sticks, plant stalks, and other large

items of debris from entering the system. Two or more screens, of progressively finer mesh, can be used when heavy loads of debris are expected. The accumulated trash must be removed from the screens before water flow to the pump becomes restricted.

Desilting basins may be required to trap sand or suspended silts when the water comes from streams or open ditches. Sometimes desilting basins and debris screens can be built as a combination structure. Desilting basins should be large enough to provide protection for at least one full day. Larger capacities are desirable.

Booster pumps should be used to provide adequate pressure for small areas that lie at elevations considerably above the principal area to be irrigated. The use of the booster pumps removes the need to carry high pressures from the main pumping plant for the relatively small fraction of the total discharge that is needed on the high area. The requirements should be determined by comparing the annual costs of using a low-head main pumping plant (plus one or more booster pumps) with the annual costs of a higher-head main plant with no booster pumps.

Takeoff valves generally are needed to control pressures in the lateral lines. The valves always should be used in systems where there are significant differences in main line pressures at the various lateral takeoff points. In multiple-lateral systems, they also permit moving individual laterals without shutting down the entire system.

Flow-control valves to regulate the pressure and discharge of individual sprinklers may be helpful when unevenness of the ground causes an unequal distribution of pressure along the laterals. They seldom are needed on level fields or smooth slopes.

Side-roll laterals, either hand propelled or power driven, can be used in irrigating forage crops on smooth, rectangular fields of well-drained soils. The laterals are mounted on wheels with the pipeline as the axle. A length of flexible hose is used to make the connection to the main line. Side-roll laterals cost more than conventional quick-coupled portable laterals, but less labor is needed.

Pull-type laterals, which are moved by towing the pipelines lengthwise with a truck or tractor, are used to irrigate forage crops and to some extent for irrigating orchards. They operate best on sandy soils that remain firm when wet. The lateral lines are supported on skids or on wheeled carriages and are towed on a curved route, which moves them into the new lateral position as the line is pulled forward. One or two lengths of pipe at the end of the lateral usually must be moved into place by hand. Labor requirements are low with this type of system, but crops may be damaged if lines are pulled across muddy fields. Under ideal conditions, one man can move a lateral one-fourth of a mile long in less than 15 minutes. Initial costs are higher than for conventional hand-move portable laterals, but usually are less than the cost of side-roll laterals.

FACTORS THAT INFLUENCE the layout and the operation of sprinkler systems must be considered in order to develop sound designs. An inventory of the land and water resources and an analysis of the conditions under which the system will be operated are needed first.

The soils must be surveyed and mapped to show significant differences in water-intake characteristics or in the available water-holding capacities. Systems may be designed to apply water at rates less than the maximum rate of intake into the soil. A knowledge of the intake abilities of the soils under the expected land use and cropping conditions, however, is needed to determine the application rates that can be used safely. Some soils take in water at rates as low as 0.1 inch an hour and others at rates of more than 2.0 inches an hour. Coarse-textured, sandy soils usually have the highest intake capacities. Fine-textured clay soils usually have the lowest. Soil structure, com-

paction, cementation, alkali, or other factors, however, may have a great effect on the intake ability of soils of any texture. Intake characteristics can best be determined by measurements made under actual operation.

The available water-holding capacities of the soils limit the amount of water that should be applied at any one irrigation. Coarse-textured, sandy soils will hold a limited amount of water available for plant use. Their capacity may be as little as one-fifth of the amount that is held in a fine-textured loam soil of equal depth. Loam soils may hold as much as 2.5 inches of available water to a foot of soil depth, but very coarse soils may have capacities as low as 0.5 inch per foot. In both instances, water must be applied before all of the available stored moisture has been used by the crop.

Topographic conditions must be investigated to determine the general land form and to determine the maximum differences in elevation. Sprinkler systems should be laid out with laterals running across the slope, as nearly on the level as possible, to minimize variations in pressure. If that is not feasible, laterals should be run down slope, so the gain in head will offset or partially offset the pressure loss due to friction in the lateral. Major modifications in design often are required to provide adequate system layouts on rough or rolling land.

Extreme differences in elevation within the area, or between the water supply and some part of the area, will have considerable effect on the power requirements of the system. Selection of pipe sizes for main and lateral lines also may be affected by differences in elevation.

Water supplies, including source, quantity, and quality, should be investigated as an early step in the design of a sprinkler system. A source near the center of the area will mean the most economical combination of pipe sizes. A source near one edge or outside the area usually will require the use of larger mains and may take more pipe.

The total amount of water available for the irrigation season is important in determining the acreage that can be irrigated. The day-by-day availability of the supply also is important in the design of a system to meet the peak-period, consumptive-use needs of the crops. If water is available on a continuous, constant-flow basis, the total seasonal amount may be adequate, but the flow may be inadequate during the periods of greatest use. Sometimes the fluctuations in demand can be reduced by cropping schedules that include crops with different peak-use periods.

Sources and costs of power have a marked bearing on the design of the sprinkler system. Limitations in phase, voltage, and horsepower should be investigated when electric power is to be used. Single-phase, low-voltage transmission lines will not furnish enough power for large systems. Motors on these lines usually are restricted to about 5 horsepower.

The type of farming also must be considered. Different crops may require different amounts of water and different irrigating schedules. Orchards and vineyards impose limitations on sprinkler-system layouts, sprinkler spacing, and types of sprinkler heads. Field boundaries, acreages, and types of crops should be determined. The direction and spacing of any tree rows or the other fixed plantings should be mapped. Cover-crop programs and their effect on peak water-use requirements also should be considered.

Climate is always a factor. Natural precipitation may furnish a large part of the moisture required by crops in humid areas. Also, peak water-use rates are much lower on the relatively cool coastal plains and in the high intermountain areas than in the hotter and drier interior valleys. Wind conditions in some places require special attention. Sprinkler spacing, nozzle sizes, nozzle pressures, and lateral layouts may need to be adjusted to provide adequate water distribution. Under adverse conditions, special wind nozzles sometimes are required. Climate

also affects the minimum rate at which water should be applied. Application rates as low as 0.10 inch an hour may be satisfactory in cool, humid areas where the wind velocity is low. They are much too low for hot, arid, and windy interior valleys, because most of the water would be lost by evaporation and wind drift. Field crops in the hot, dry, southern areas may require minimum application rates approaching 0.5 inch an hour.

Farm schedules need to be considered. Irrigation cycles and the movement of irrigation equipment should be designed for minimum interference with cultivation, spraying, harvesting, or rotation-grazing schedules. Adjustments in the amount and frequency of applications or use of extra equipment may be required to fit irrigation into the overall farm operating schedule.

Availability of labor may influence the design length of sets, or call for the use of special equipment. Small systems usually are designed for either one or two sets every 24 hours, and the sprinklers are moved in the morning or evening, or both, as a routine chore. More frequent moves are common on the larger systems, where the amount of pipe to be moved is sufficient to justify the employment of full-time irrigators and where the soils can be irrigated safely at higher application rates. Sometimes labor requirements are reduced by using wheel-mounted or tractor-towed lateral lines.

Good design is essential to the successful operation of a sprinkler irrigation system. That is an engineering job. Systems should be purchased from a dealer who will follow adequate engineering standards. The American Society of Agricultural Engineers and the Sprinkler Irrigation Association have developed a list of minimum requirements for the design, installation, and performance of sprinkler-irrigation equipment.

A well-designed system should meet the following conditions:

Apply water at a rate that does not cause runoff during the normal operating period or cause water to stand on the surface of the soil after the sprinkler line is shut off.

Have a capacity that is large enough to meet the peak moisture demands of all crops irrigated within the area for which it is designed. The system must be large enough so that one irrigation can be completed before it is time to start another.

Avoid crop damage. Different crops may require variations in sprinkler heads and operating pressures, such as the use of the low-angle sprinklers for peaches, apricots, and cherries.

Provide operating pressures that comply with the recommendations of the manufacturer of the sprinkler. The variation in pressure between any two sprinklers or sprinkler locations on the field should not be more than 20 percent of the higher pressure, regardless of elevation and friction losses. This will hold the variation in sprinkler discharge to about 10 percent.

Apply the amount of water that the soil can hold for use by the crop. When the system is designed and operated correctly, there should be a minimum of overirrigation or waste of water. However, the system must be able to supply adequate water to wet the root zone to the depth specified for the soil and crop under consideration.

Provide pipe sizes that are economical to install and operate. Pipe that is too small requires extra power to overcome the high friction loss. Pipe that is too large makes the purchase cost too great.

Have a matched pump and power unit that is designed to do the specific job at hand. The pump should operate near its maximum efficiency. Poor equipment often increases operating expenses more than enough to offset any savings made in the original purchase.

The operation of sprinkler irrigation systems in accordance with the standards used in the design is essential. Systems are designed to apply a given amount of water to a specified

area of known soils and crops. Any attempts to expand the system to include additional acreage or to use it on an area of the same size but with different soils or crops usually will result in unsatisfactory performance.

Prescribed operating pressures must be maintained, since variations in pressure will cause changes in amounts and rates of water application.

The length of time for each lateral setting should be determined by the amount of water needed to bring the soil up to field capacity. Quite often the time required will be less than the maximum time for which the system was designed. That will be true particularly during the early stages of plant growth. Those lateral settings of less than the design time should be made when necessary to prevent over-irrigation and waste, but the design time of the lateral setting should not be exceeded, since such a procedure might result in failure to cover the entire field before part of the crop is damaged by lack of water.

Irrigation must be started on time in order to prevent damage to the crop on the portion of the field that is irrigated last. Late starts mean decreased production. An examination of the soil profile to determine moisture content will indicate the proper time to start irrigation.

MAINTENANCE ESSENTIALS for most sprinkler systems are relatively simple. Periodic inspection and replacement of worn parts are needed. Special attention should be given to pumps, motors, and internal-combustion engines and to safety devices such as low-pressure and high-temperature cut-off switches. Foot valves, check valves, debris screens, and desilting basins should be cleaned frequently. Portable pipe and pipe couplers need little attention other than occasional repair or replacement of rubber gaskets and repair or replacement of pipe accidentally damaged. Revolving sprinkler heads should be inspected annually for worn or damaged bearings and repaired or replaced as needed. Sprinkler nozzles may be eroded by the high velocity flows through them, especially if any fine sand or silt is carried in the water. As these enlarged nozzles will discharge more than the designed amount of water or cause a decrease in pressure, they should be examined occasionally and replaced as needed.

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Applying Water Under the Surface of the Ground

George M. Renfro, Jr.

In subirrigation one applies water beneath the ground surface rather than on it—usually by creating and maintaining an artificial water table at some predetermined depth. Moisture then reaches the plant roots through capillary movement upward.

For successful subirrigation, an adequate supply of water of good quality must be available throughout the growing season. The topography must be nearly level and smooth. A layer of soil must exist immediately below the surface soil which is sufficiently permeable to permit the free and rapid movement of water laterally and vertically.

A barrier against excessive losses through deep percolation must exist in the soil profile. The barrier may be a relatively impervious layer in the substratum or a permanently high natural water table on which an artificial table can be built. The distribution system must consist of a well planned system of main ditches, field laterals, and

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structures, which will permit the water table to be raised to a uniform depth below the ground surface over the entire area. An adequate outlet for the drainage of the irrigated area must be available or provided for, particularly in humid areas.

In only a few places in the United States do all those conditions exist together. The use of subirrigation therefore will always be limited. Among the places where subirrigation is practiced are the following: The Sacramento-San Joaquin Delta in central California; the Everglades of southern Florida; the San Luis Valley in Colorado; the Flatwoods of the Florida Coastal Plain; the Cache Valley in northern Utah; the Egin Bench in southern Idaho; smaller, scattered sections in Kansas and Nebraska; and in the organic soils of the Great Lakes States of Michigan, Indiana, Minnesota, and Ohio, where the practice is known as controlled drainage, since the water table is controlled by a system of structures in drainage canals and additional irrigation water is not normally employed.

The principles involved in subirrigation are the same in all areas, although the means of introducing water into the soil profile may differ. An artificial water table is created over a natural barrier that prevents deep percolation of the water. The water table is kept at a fixed depth, usually 12 to 30 inches, below the surface.

Water may be introduced into the soil profile through open ditches, through mole drains, or through tile drains. The first way is most widely used because it is relatively inexpensive and is adaptable to all the soil types that can be subirrigated. Mole drains can be used only in organic soils. Tile drains are used in connection with subirrigation to a limited extent in the organic soils of Michigan, Indiana, Minnesota, and Ohio and in the sands of the Flatwoods area of Florida. Tile drains may cost several hundred dollars an acre—usually too much for all but high-value crops.

The method is further explained in the following discussion of some areas where it is used.

The Sacramento-San Joaquin Delta of California covers about one-quarter million acres, made up entirely of peat, at the confluence of the Sacramento and San Joaquin Rivers. The area consists of more than a hundred tracts and islands, each organized into one or more reclamation districts under State law for the construction, maintenance, and operation of levee and drainage systems. About 160,000 acres there are subirrigated.

The ground is level. Before reclamation, the elevation of all the peatland was near sea level. Because of subsidence, the surface has dropped 6 to 8 feet since 1922, and much of it is now between 10 and 11 feet below sea level. Each of the tracts and islands is surrounded by a levee, which keeps out floods and tidal overflow.

A typical soil profile in the area may be described thus:

0–23 inches, tule-reed muck. The surface organic material, to a depth of 8 inches, is cultivated organic residue, grayish black, granular, friable, and more or less neutral in reaction. Between 8 and 23 inches below the present surface is a rather dense, heavy-textured, dark, grayish-brown, tule peaty muck.

23–28 inches, yellowish-brown, matted, poorly decomposed, fibrous reed peat, commonly referred to as buckskin peat.

38–72 inches, grayish-brown tule peat, in part sedimentary fibrous.

72–96 inches, brown, fibrous, or matted fibrous, partly decomposed, tule reed peat.

96–114 inches, yellowish-brown, reed peat characteristic of a floating mat.

114–120 inches, grayish-brown, structureless, sedimentary peat, which developed from plant communities that occupied open water. The underlying mineral material is a gray, compact, sticky clay.

Because the Delta has only moderate rainfall—12 to 20 inches—most crops

require irrigation. Water is siphoned over the levees from the surrounding stream channels into open ditches, which parallel the levees about 100 feet inside the inner toe. The water is discharged into lateral ditches that dissect the islands or tracts into fields of 20 to 40 acres. The lateral ditches are 4 or 5 feet deep, 3 feet wide at the bottom, and 5 to 6 feet wide at the top. From the lateral ditches, smaller spud ditches lead the water down the crop rows. The spud ditches are about 10 inches wide and 18 to 20 inches deep and are spaced in accordance with the requirements of the crop. For potatoes, the spacing is usually about 20 rows apart. The spud ditches are redug with a small trenching machine each year after the crop rows can be seen; the excavated material is spread out on both sides so as not to disturb the crop.

The ground-water table is raised to the desired height and maintained there by means of dams in the lateral ditches and baffles in the spud ditches, which keep the water level in the spud ditches at nearly the bank-full stage. Lateral movement of water from the spud ditches allows the water table to be raised and maintained.

The same system of ditches is used for drainage. Excess irrigation water, water that seeps through the levees, and excess water from winter rains are carried in the same ditch system to drainage canals, which carry the water to a pumping plant. The water is lifted over the levee and discharged into the surrounding stream channels by automatically controlled electric pumps.

The main crops so irrigated are potatoes, asparagus, beets, onions, celery, and corn. The water table is maintained at different levels for different crops and for different stages in growth of the same crop. For instance, for celery the water table is held very near the surface; for other crops it is held somewhat lower.

Subsidence is a major problem in the cultivation of peat lands. Several factors may have some bearing on the lowering of the soil surface in the Delta: Geologic subsidence of the entire area, compaction by tillage machinery, shrinkage from drying, oxidation, burning, and wind erosion.

The fact that the entire peat profile, to depths of 30 feet or more, is made up of the remains of plants very similar to those that now grow on the surface seems to indicate that the surface has been rather constantly at or about sea level. Tules and reeds do not normally grow in water 30 feet deep. It would seem more likely that the growth of tules and reeds kept pace with the receding substratum.

The Delta region is owned and farmed in large tracts. From the beginning of cultivation, the use of heavy farm equipment has been a common practice. A heavy tractor passing over these soils will shake the surrounding area for a radius of 200 feet or more. Undoubtedly some compaction of the surface soil is caused by cultivation. For instance, when "buckskin" is exposed, and the soil is worked down to a condition for planting, the surface is about 2 feet lower than it was in its original state. The theory that cultivation is responsible for subsidence is less acceptable than formerly, however. If any considerable portion of the subsidence were due to compaction, there would be a marked increase in volume weight of the surface soils as compared with the subsoil.

(A more complete discussion of the drainage and management of peat and muck soils and of subirrigation in the Florida Everglades begins on page 539.)

With the approach of each dry summer when stream runoff is scant, the waters in the stream channels surrounding the tracts and islands temporarily become increasingly saline. In a few recent years, the limit of salinity in irrigation waters permissible for plant growth has extended well inland. At such times, growers suspend the late summer irrigations from affected channels.

The general practice of subirrigation promotes the concentration of salts in the surface soil, where it hinders crop

production. The organic soils are extremely permeable and have a high ability to hold water. Salt-laden moisture rises rapidly in them during the drier seasons because of the high water table. When adequate underdrainage is maintained, the winter rains tend to wash much of the surface accumulation of salts downward in the soil profile. If the movement of soil moisture could be maintained predominantly in a downward direction, little or no accumulation of salts would result.

THE SAN LUIS VALLEY OF COLORADO is a large mountain valley in the south central part of the State along the upper reaches of the Rio Grande River. The river enters the valley at about the center of the west side, flows generally east-southeast for about 30 miles, and then flows south out of the valley. Immediately north of the river is a divide, which cuts off water entering the valley from the north; thus the northern half of the valley has no natural surface or subsurface drainage outlet.

The valley was once an arm of the ocean and later became an inland lake. Alternate layers of sand, gravelly sand, and sandy, gravelly clay were deposited in the lake. As the area is surrounded by mountains and has barriers to lateral drainage, the valley is a huge artesian basin.

The subirrigated part comprises approximately 135,000 acres in its west central part, near the towns of Center and Monte Vista.

The topography of the land is generally flat, sloping from 7 to 15 feet per mile from west to east. There is very little slope in the north-south direction. With proper handling, water can be conveyed north, east, or south from nearly any point in the area. The surface of the land is not smooth enough for efficient subirrigation, and the landowners therefore spend from 35 to 65 dollars to level an acre.

A typical soil profile in the area has a gravelly, loamy sand to light, sandy loam surface, which may be 6 to 30 inches deep and is underlain by a gravelly sand or sandy gravel of varying depth. At depths of 30 to 60 feet, the top retaining clay layer of the artesian beds is encountered. The layer also acts as the base for the subirrigation water.

The Rio Grande is the main source of irrigation water in the part of the valley that is subirrigated. Some water comes from wells and artesian flow.

The distribution systems consist of canals, laterals, and field ditches, the same as are used generally for surface irrigation. Subirrigation ditches are spaced 50 feet to 75 feet apart for the lengths of the fields. They are kept filled with water, and the resulting rapid lateral movement of water in the soil profile maintains a reasonably uniform water table level between ditches.

An effective drainage system has to be provided so that the water table can be lowered rapidly when necessary and harmful salts can be leached out of the profile. Checks are required in the drains; they must be close enough together to maintain the water table at a uniform depth below the water surface. Slope and soil texture govern the spacing.

Potatoes, small grains, vegetables, alfalfa, sweet clover, and native hay crops are irrigated. For potatoes, small grains, and vegetables, the water table is maintained at a depth of 18 to 24 inches. Every effort is made to prevent vertical variations in the water table from day to day throughout the season. Alfalfa is not generally subirrigated as such, but does receive an early season flooding and a late fall flooding. Initial seedings of alfalfa are usually with small grain as a nurse crop and the depth to the water table is determined by the needs of the small grain.

The meadows of native hay normally lie at a slightly lower level than the cultivated land and are constantly flooded with whatever water is available after irrigation of the cultivated land. The water table is maintained at or near the surface through as much

of the growing season as is possible. During the late growing season and winter, the depth to the water table may be 8 to 15 feet because of a lack of water.

Irrigation losses on individual fields are high. Because the water lost on one field is used to raise the water table on lower fields, however, the irrigation efficiency of the total area is relatively high. No reliable estimates of water used in the subirrigated area are available, but the river diversions for all irrigated lands are approximately 2 acre-feet per irrigated acre per year.

That is efficient use of water in most areas, and especially efficient in an area with less than 7 inches of annual rainfall.

One of the major problems is lack of control of the supply of water. Early in the season there may be more water than is needed, and many areas are indiscriminately flooded to help raise the water table to the desired level. As the season progresses, the supply of water diminishes and more care is used in applying water. The crops of lower value suffer first from lack of water. After the middle of the season, all crops suffer from lack of water, and it is not possible to maintain a proper water table level for subirrigation. Lack of storage reservoirs at the edge of the mountains is an important cause of poor control of the water supply.

A second major problem is the accumulation of soluble salt and sodium. The situation is a strange one: Farmers try to maintain a high water table because the soil is so light in texture it would not produce well otherwise, but at the same time they maintain extensive systems to drain out the harmful salts. The system of alternating the subirrigation and drainage is known to be beneficial, and the farmers are continuously improving their methods.

THE FLATWOODS of the Florida Coastal Plain contains many areas where subirrigation is practiced. It is a large area along the Atlantic and Gulf coasts of the Florida peninsula and many miles inland. Unlike the areas I have mentioned, subirrigation in the Flatwoods is not generally practiced as a group enterprise on a large area containing many adjacent farms, but is undertaken on an individual basis. Thus the individual areas irrigated are widely scattered. The practice of subirrigation has expanded rapidly, particularly in connection with the development of improved pastures.

The topography is level to nearly level. Slopes seldom exceed 2 feet in 100 feet. The surface is usually sufficiently smooth that land leveling is not needed.

While the different soil profiles vary considerably, all are moderately deep to deep, poorly drained sands, with a permanently high water table that varies in depth from near ground surface in the rainy season to as much as 5 feet below the surface in the dry season.

A typical profile description of Leon fine sand, one of the principal soils subirrigated, is:

0–9 inches, very dark gray, compact, fine sand, containing considerable black organic matter.

9–24 inches, light gray, compact, fine sand, with a very low organic content.

24–30 inches, black, very compact, dense, fine sand, with considerable organic matter, semiendurated into a typical organic hardpan.

30–72 inches, brown, compact, fine sand.

The permeability of the 9- to 24-inch layer is rapid, and water can move freely and laterally for both irrigation and drainage.

The permanently high natural water table and the rapid lateral movement of water in the profile make subirrigation possible. An artificial water table is built up in dry seasons over the naturally high water table to a height that will provide adequate moisture in the root zone through capillary action.

Water may be obtained from wells, streams, and some natural lakes. The peninsula of Florida has a good supply of artesian ground water, which can be

obtained in quantity at economic pumping depths. Many wells flow freely without pumping.

When ground water is used, the wells are located at the highest points in the area to be irrigated. When streams or lakes are used, the water must be pumped and conveyed to the highest points through pipes or between dikes. Water is sometimes conveyed in channels below ground surface with low-lift pumps employed to raise the water at the high points in the area to be irrigated. Topography determines the method of conveyance used. The water is then distributed by gravity to all points in the irrigated area through a system of main ditches and field laterals.

The field distribution systems differ in layout, depth, shape, and spacing of the main and lateral ditches, depending on the type of crop. Potatoes, many vegetables, and pasture grasses are subirrigated in the Flatwoods.

For subirrigating improved pastures, the main ditches are usually trapezoidal and contain check structures equipped with flashboards to control the water level. As the ditches are used also for drainage, their depths and cross-sectional areas often are determined by the volume of water that must be removed from the drainage area. The structures are spaced at vertical intervals not exceeding 6 inches. The flashboards are removed during the rainy season, June to October, to allow adequate drainage.

Field laterals are V-shaped ditches, not less than 18 inches in depth and 8 feet wide. They are staked out on the contour or as nearly so as is practicable. Their length is usually limited to 1,200 feet. The horizontal spacing of the field laterals varies between 60 and 200 feet, depending on the soil characteristics that govern the rate of lateral movement of water and on topography. The vertical interval between laterals should not exceed 6 inches and should be considerably less in order to maintain a reasonably uniform depth to the water table in the irrigated area.

Flashboards are inserted in the main ditch structures to a height that will maintain water in the field laterals at or near bank-full stage. This stage is maintained until the water table rises to within 12 inches of the surface and until capillary action brings the moisture level in the top 12 inches of soil to field capacity. The water is then cut off, and the water table is allowed to recede by plant use and by evaporation and other losses until a depth of 24 inches below the surface is reached. At that depth, water is again applied, and the procedure is repeated.

The entire system, when adequately planned, installed, and maintained, provides excellent drainage during the rainy season.

The minimum flow required for efficient operation of the systems is about 7.5 gallons a minute an acre irrigated if the systems are operated for 24 hours a day. Most farmers and ranchers, however, prefer to confine irrigation operations to daylight hours; then a minimum flow of about 15 gallons a minute is required.

The efficiency of water use varies considerably among the farms and ranches, depending on soil characteristics, topography, and on the kind of operation and management. In good systems the efficiency is 70 to 75 percent.

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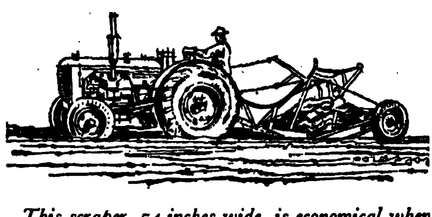

This scraper, 54 inches wide, is economical when cuts are not too heavy and hauls are short, but a large scraper unit does the job faster. (*See page 283.*)

Preparing Land for Efficient Irrigation

J. G. Bamesberger

On many farms three-fourths of the irrigation water is wasted. A good way to prevent such waste is to prepare fields properly before they are irrigated.

The preparation of land for irrigation—or land leveling, as it is commonly called—is the reshaping of the land surface to facilitate or improve the uniformity of application of the water. It includes grading or shaping the surface to any desired slope as well as the formation of an actual horizontal plane.

Generally the reshaping is done to provide uniform grades or to reduce grade in the direction of irrigation or at right angles to it. Sometimes the grade of a field is increased or grading was done so the direction of planting could be changed. Land preparation in humid areas is needed to provide surface drainage and to achieve more even penetration of irrigation water and rain.

Because of differences in soils, slopes, or the farmer's wishes, not all fields are given smooth surfaces. Land preparation may consist only of removing a part of the high spots and filling a part of the low places. It may bring only a minor improvement in the land surface and slight improvement in irrigation efficiency. Or it may be possible to reshape a field to the extent that beneficial use can be made of all the irrigation water and much of the rainfall.

Many irrigation workers in the Southwestern States have used a classification of types of land preparation. It is based on the effectiveness of different forms of land surfaces in improving the uniform application of water.

Six types are classified, starting with rough grading (type 1), then variable grades in all directions (type 2), up through uniform irrigation grade with side slope (type 3), level transversely with a variable irrigation grade (type 4), and with a uniform grade (type 5), and finally to exactly level in all directions (type 6). The first three types permit side slope. The others require that the land be exactly level at right angles to the direction of irrigation. The classification has proved to be useful, and something like it would be of value in all irrigated areas.

If we acknowledge that there are different types or degrees of efficiency in land preparation, we recognize that the farmer or land operator must make a choice of type when he undertakes land leveling. We say generally that the highest type of land leveling suitable to a field should be adopted, but there are situations in which something less will be satisfactory and more practical.

THE LAND SLOPES, kind and depth of the soils, climate, crops to be grown, water supply for each field, economic considerations, and the farmer's preferences all have to be evaluated in designing any job of land preparation.

If the land is very rolling, steep, and irregular and the soils are shallow, it may not be possible to shape the surface to uniform slopes on good irrigation grades. Successful irrigation farming can be practiced on land of steep and nonuniform slopes, but that land should be kept in pasture as much of the time as possible in order to prevent severe soil erosion.

The development of a uniform grade only in the direction of irrigation often may be the highest practical type of land leveling. That is especially true of fields that have little cross slope, where the crops will always be irrigated by the furrows or corrugations. In orchards especially, this type of leveling is satisfactory.

Some extremely irregular fields or irregular fields with shallow soils will not permit use of a higher order of land preparation. Only a study of the cuts that will be required for better leveling can determine this, but often they will

be so great that too much earth will have to be moved or the fertile soil will not be deep enough to allow the cuts to be made without exposing too much infertile subsoil. On the other hand, a high type of leveling often can be done on fields with rather shallow soil if the slope is gentle and the surface already nearly smooth.

Grading the land to a uniform slope in the direction of irrigation and removing all slope at right angles to it should be the result of most leveling jobs, particularly when irrigation is to be by flooding. A good irrigation grade, designed in accord with the infiltration rates of the soil, the size of irrigation streams available, the crops to be grown, and the erosion hazard from rainfall, permits uniform distribution of water and is particularly important in this type of leveling.

Land graded to an exact level—no slope in any direction—permits the most efficient irrigation. Only the actual amount of water needed can be put on the land so there is no waste through runoff, but it is not practical for all fields. Its cost is high and its use is limited to sites where the available streams of water are large enough to force the water the entire length of the irrigation run before much moisture soaks in at the inlet end. Nor is it suitable for humid areas, where at times excessive rainfall must be drained off the fields.

Types of land preparation that permit a cross slope at right angles to the direction of irrigation are more adaptable to an entire field than are the types in which all cross slope must be removed. Usually excessive cuts are necessary to eliminate the cross slope. That may be too costly or require cuts that expose large areas of infertile subsoil. Therefore, if these more advanced types of reshaping, which eliminate the side slope, are desired on sloping ground, the field often is divided into parts and the leveling is done in strips—or "lands"—at different elevations, separated by low ridges or borders. It is commonly called bench leveling, especially if there is a considerable difference in elevation between adjacent strips. Such benches may be rectangular or they may have curved boundaries.

The width of the benches will be influenced by the farming equipment to be used, the available irrigation stream, and the amount of earth work involved. The amount of earth work, in turn, is governed by the original slope at right angles to the direction of irrigation. Depth and character of soil will naturally limit the depth of cut and consequently the width of the bench.

Leveling jobs cannot be changed easily once they have been completed, so every precaution should be taken to insure that irrigation grades, runs, and streams are so adjusted that the field can be uniformly irrigated. The only way to avoid guessing is to get the information from actual field tests. Measuring the rate of moisture penetration, soil movement, and uniformity of rate of water flow will furnish the information needed to select a proper grade and length of run for a particular soil. The importance of making those determinations in the field, as a basis for the design of the layout, cannot be overemphasized.

The selection of the type of leveling and the layout of various fields should always take into consideration the crops to be grown throughout the complete rotation. Widths of borders and benches should be adjusted for the use of standard farm implements. A bench on which grain is to be grown, for example, should be some multiple of the width of the grain drill. When possible, benches should be made uniform in width, as too much variation means uneven irrigation. Some farmers select the minimum acceptable width so that the difference in elevation between benches will be kept small and less earth will have to be moved. Many others prefer to make the benches as wide as possible, so as to interfere less with farming operations.

The relation of benefits to costs of

land preparation influences the selection of type. If at all possible, the most efficient type suitable to a particular field should be selected and planned at the start and built with as little delay as possible. That usually is less costly in the long run than doing the work in successive steps and taking several years to finish the job.

A direct relationship exists between the methods of irrigation and the increased efficiency in the use of irrigation water that land preparation can bring. Some methods of irrigation may be inefficient and because good land preparation can improve them only slightly, expensive land preparation cannot be justified. So, besides the restrictions imposed by physical limitations, the choice of a type of land preparation should be governed somewhat by the method of irrigation that will be used.

Basin irrigation floods a more or less square area rapidly with the desired amount of water. It can be effective in getting a uniform application if properly designed. Consequently a high, rather costly type of land preparation can be justified. Basins are usually exactly level, or at least level in one direction with a very little cross slope.

It is not, however, a satisfactory method in areas of high rainfall unless the excess can be drained off the fields to prevent damaging ponding of water.

Borders, which are long, narrow basins, also can be used effectively to accomplish uniform irrigation. Because the water has to flow the length of the border, some grade is usually provided in the direction of irrigation. The amount of slope that is provided depends mainly on the available irrigation stream, the soils, the climate, and the crops. The best type of land preparation for border irrigation is a uniform slope in the direction of irrigation with no cross slope. The highly efficient use of irrigation water possible with border irrigation justifies the cost of land preparation. Here again, excessive rainfall will be a problem in humid areas and enough slope must be provided to remove all excess water.

Furrows are used to distribute water over fields and can do so effectively in a well-designed and well-managed layout. Furrows should have a uniform grade throughout their length to be most effective or they may be level, but some cross slope in the field is not detrimental. If furrow irrigation alone is to be used, the highest types of land preparation seldom should be selected. Crop rotations used on most fields include both row crops and close-growing crops, however. So, since border irrigation is the best way for irrigating close-growing crops such as alfalfa, border irrigation criteria will usually govern the selection of a type of land preparation even though furrow irrigation would be the method under immediate consideration.

Irrigation by corrugations, which are small and closely spaced furrows, is generally a good deal less efficient than furrow, border, basin, or sprinkler irrigation. That is largely because of the difficulty of equalizing the flow in many small channels and keeping the corrugations free of obstructions to prevent them from breaking over into adjacent corrugations. Also, corrugations are so shallow that there must be a minimum of slope at right angles to their direction. Thus the irrigation is directly down the steepest slope. Unless fields are practically uniform to start with, a land preparation layout of a high type, such as uniform grades with no cross slope, adapted to irrigating directly down slope, will result in cuts and fills of such size that the work will not be feasible. Furthermore, the possibility of improving the distribution of irrigation water to any great degree is not sufficiently promising to justify a high type of leveling if it involves a significant increase in cost. Grading to a fairly uniform slope is probably the best that should be undertaken if irrigation by corrugations is to be continued.

Wild flooding does not use dikes to guide the flow of irrigation water. The water is distributed over the field by

the irrigator as best he can. It is an inefficient method, and land preparation will do little to help the irrigator to do a better job. Rough grading and smoothing is about all the leveling that can be justified until a better method replaces wild flooding.

SURVEYS, MAPS, AND ENGINEERING are needed to develop a good plan, and land preparation may not be of much value unless it is done according to a good plan. Many fields appear smooth to the eye but are too uneven to apply irrigation water uniformly.

A soil survey should be made before leveling is done. The map the soil surveyor prepares will show the nature of the soil, the subsoil, and the materials under the subsoil. It will show the depth to sand, gravel, caliche, rock, or other materials that might limit the depth of the cut, as well as the extent of such areas. Alkali spots will be outlined and the depth to water table shown. That information will help the engineer to plan the best layout for leveling. In some instances, cuts into the subsoil will not be harmful because organic matter and fertilizer can be added to build up its productivity quickly. In other instances, the engineer learns that if he removes the surface soil, he will expose inert material, which will not grow crops. Soil surveys also furnish information relative to infiltration rates and permeability. If the subsoil and substratum are sand or sandy loam, and the infiltration rates are high, the irrigation runs must be shorter than if there is clay loam or clay underlying the surface. For best results the engineer must team up with crop specialists and soil scientists. They must all see the problem the way a farmer does.

Land leveling is a technical procedure. Time and time again it has been proved that the eye alone is not good enough to do a first-class job of leveling. Accurate leveling can be done only through the use of surveying instruments in the hands of technicians.

A topographic survey and a map should usually form the basis for preparation of a plan and layout. Besides showing the shape and size of a field, the map should show surface topography, proposed surface elevations and irrigation layout, and, where they exist, the drainage facilities. How detailed the map should be will depend upon the regularity of the surface and the degree of refinement or type of work proposed. The better the type of land preparation to be undertaken, the more refined should be the studies and the work of layout and supervision.

The type of many leveling jobs can be selected as soon as the field or farm has been looked over and some preliminary observations made. But more detailed surveys and investigations often are necessary before final choice is made.

In planning a field to be leveled, it is helpful to square up the layout with permanent ditch locations, fence lines, or property boundaries as much as possible. Sometimes it is necessary to lay out borders and irrigation runs diagonally across a field. That complicates the location of field ditches, makes irrigation more difficult because of varying lengths of runs, often increases farming problems, and also results in some loss of land at the ends of borders or crop rows. By relocating ditches and field fences, however, it is often possible to have a better and more economical plan for land leveling and irrigation in which the field boundaries are square with the irrigation layout.

After the design is complete, estimates can be made of the earthwork and its costs. It is important that the farmer have a record of the estimates made by the engineer. Everyone concerned should know exactly what the plan of work is and how it is to be performed. On larger jobs and particularly on contract jobs, plans should be accompanied by written specifications, however brief. Contract jobs also should be covered by at least an informal but written agreement between the farmer and the contractor.

CONSTRUCTION can be carried out with various pieces of equipment. Leveling must be finished to the given grades. Obtaining an economical and workmanlike job depends not only on the right kind of equipment, but also on the skill of the operator.

Land leveling is done most effectively with tractor-drawn or motor-propelled equipment. The carryall is used widely. It is an efficient machine.

It cuts to grade, spreads the dirt evenly, and hauls economically for fairly long distances. Carryalls have capacities of 3 to 30 cubic yards. They almost always require more power than is available from farm tractors.

Smaller wheeled scrapers, which can be used with farm tractors, are in common use for leveling land. They will move the earth just as cheaply as large equipment, but they take more time to get the job finished. Under most conditions, the carryalls and wheeled scrapers can be used to cut without first plowing the ground. But sometimes it is necessary to loosen tight or hard soil by ripping before using land-leveling machinery.

Bulldozers are used for rough grading but are not efficient for fine grading or for moving earth beyond 200 feet. Graders, terracers, or maintainers are frequently used to move earth short distances sideways, but the cost per yard is fairly high, even for short moves.

Leveling jobs are finished with levelers, floats, or land planes rather than with heavy earth-moving equipment. The land plane has four wheels and an adjustable blade located at about the center of the frame. It is at least 60 feet long, and this great length makes it possible to finish a field to a uniform smooth surface. Large tractors are needed to pull it.

The two-wheeled automatic-type leveler ordinarily is used for fine leveling. It has a movable blade placed at about the center and so constructed that it will drag a considerable volume of dirt. It is usually less than 35 feet long, and medium-sized farm tractors can power it. It is much less efficient than a carryall for moving large quantities of earth or for moving earth long distances. The commonly used wooden float or drag is found in many variations as to detail of design. It is usually shorter than the other two types of levelers and therefore does not do so good a job of finishing.

Regardless of the type of equipment used, the work should be checked during construction. A final check should always be made after the job appears to be finished—but before the equipment is moved off the field.

For farm ditches, border ridges, and various improvements associated with land preparation and irrigation layout, other equipment is needed. Several types of ditchers will do a good job of building head ditches cheaply. Borders are made with road graders, plow, V-ditchers, disk ridgers, slip scrapers, fresno scrapers, A-floats, and other farm implements. Most of them leave a furrow or gutter along the border ridge, which should be floated out or filled up before the field can be considered finished unless the furrow is required for drainage on flat areas.

Efficient equipment for constructing and maintaining the head ditches and border ridges should be available on an irrigated farm because it is good practice to plow up the ditches and border ridges each time a field is plowed in order to kill weeds. Temporary field ditches often must be replaced during the irrigation season.

THE COST OF LAND LEVELING varies through such a wide range that a general statement about it has little value. On some lands a price of 10 dollars an acre would be too much.

On other lands, which are steep but capable of producing high-valued crops, a cost of 300 dollars an acre might be justified. It all depends on the value of the increased crop yields that can be expected from the improved irrigation.

For any who must have an average figure, a cost of approximately 50 dol-

lars an acre has been derived from records covering more than one-half million acres of land preparation in the Southwest. The records show that small, light equipment powered with farm tractors could do the leveling at no higher cost than big, heavy equipment but took a much longer time to complete the work. The cost of land preparation done by contract or the cost when it was done with the farmer's own equipment were nearly the same.

Maintenance of leveled land is required in order to keep it leveled. Perennial crops, such as alfalfa, should not be planted immediately after leveling. Since fills will settle and leave the ground surface uneven when water is applied, it is better to plant an annual crop the first year. When the crop has been removed, the low spots should be filled in by floating and the entire field put into final shape before a crop that will occupy the field for several years is planted.

If the leveling operations have exposed infertile subsoils, it is a good plan to plant a green manure crop the first year. This should be plowed under to add organic matter to the soil. As a rule, it will be necessary to add some commercial fertilizer since the areas from which the topsoil has been removed will be much less fertile than the original topsoil. A heavy application of barnyard manure may be used in place of a cover crop.

It is usually beneficial to plant a row crop after the green manure crop or during the first year. Cultivation tends to mix the disturbed soil, loosen the areas that have been compacted by leveling machinery, allow air to enter more readily, and make conditions more favorable for soil bacteria.

Back furrows and dead furrows should be eliminated in plowing. Plowing should not be done in a way that will continuously move the soil in one direction. Every time a field is plowed it will have to be refinished with a float or similar implement if high and low spots are to be avoided. In the lower types of leveling, regular tillage and maintenance operations provide an opportunity for a farmer to improve progressively the leveling work on his fields until he has reached the greatest practical refinement.

Maintenance is also needed on fields that are irrigated with silty water. Silt accumulations tend in time to build up the upper ends of the borders or rows. The silt is never deposited evenly, and the ground surface must be properly releveled before it becomes so uneven as to interfere with efficient irrigation.

An overall plan covering ditch locations and capacities, water control structures, cropping practices, and a tentative irrigation schedule based on best available information on infiltration rates and water-holding capacity of the soil should be developed in addition to the land leveling plan. Land preparation is only one factor in the efficient use of irrigation water. Other factors must be considered and the land-leveling plan fitted into the plan for the others if the greatest effectiveness is to be attained.

Benefits from a well-planned, well-constructed, and well-operated land preparation job are many. Leveling makes possible a more even distribution of the irrigation water through its better control and management. The result is water saved, labor saved, more uniform stands, and increased crop yields of better quality.

A rough or uneven field will be watered too little on the high spots and too much in the low spots. When too little water is applied, a crop may ripen prematurely, if it survives at all. Too much water tends to make a crop ripen late. Also, low spots remain wet for a longer time than the rest of the field, so sometimes a farmer has to cultivate around them. Sometimes he may cultivate them when they are too wet, and then puddling results. Alkali and harmful salts usually accumulate in low areas. Such spots can sometimes be eliminated by land leveling. Irriga-

tion year after year to depths below the root zone is certain to result in the loss of valuable soil elements and a drop in fertility. Too heavy irrigation on many types of land likewise hastens the day when the land has to be drained. In a properly leveled field, soil losses caused by application of irrigation water can be held to a minimum. And aside from the more tangible benefits of land leveling, the general appearance of a farm is enhanced if a good job of leveling has been followed up with other improvements in the layout of irrigation.

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Wells and Pumps for Irrigated Lands

Carl Rohwer

In much of the arid and semiarid regions of the United States, the water from streams is completely utilized for irrigation or, if surplus water is still available, the cost of bringing it to the land is too high. In those places, therefore, pumping from the great reservoir of water in the ground is the only source of additional water for irrigation.

Factors to be considered in developing successful irrigation enterprises by pumping from wells are the supply of ground water, the land, the well, the pump and accessories, the crops, and the markets.

First is the water supply. If it is inadequate or if the quality is unsatisfactory there is no need to consider the other factors.

Next in importance is the land. It must be fertile. The topography must be suitable for irrigation.

A supply of adequate and suitable ground water usually is harder to find than land that is suitable for farming. Water exists beneath the surface of the ground in most arid and semiarid regions, but conditions often are not favorable for utilizing it to irrigate crops. Sometimes it is so far down that the cost of pumping is too great. Or the formation in which the water occurs is so tight that it does not yield water readily or is so limited in extent that the supply would soon be exhausted. Or the rate of recharge of the ground water reservoir is too small to justify extensive development of the area. Or the supply may contain too much salt.

Alluvial deposits containing thick layers of water-bearing sand and gravel are most favorable for obtaining a good water supply. Broad alluvial valleys, traversed by rivers or irrigated by a network of canals, are ideal sites. The seepage from the rivers and canals and the deep percolation loss from irrigation nearly always assure adequate recharge of the ground-water reservoir. In such valleys the water table usually is quite close to the surface, an important aspect from the standpoint of pumping costs.

No hard-and-fast rules can be laid down as to the depth to water beyond which pumping is no longer feasible for irrigation. It depends primarily on the value of the crops produced. In California and Texas, where fruits, cotton, and winter vegetables are grown, lifts of 400 to 500 feet and more are common, but in other areas where general farm crops are grown, 100 feet is probably the maximum, except under special conditions. If sprinklers are used, the total pumping lifts can be higher because the amount of water required usually is less.

The water need not be potable, but it must not contain high concentrations of salts injurious to plants or soil. Water of doubtful quality should be tested to determine which alkalies are present and the percentage of each.

Most States have definite procedures for establishing the right to divert water for irrigation from streams but not for establishing the right to pump from underground sources. The laws governing pumping from wells differ widely in the States. Therefore the legal right to pump should be determined by consulting the State engineer, and, if the priority of right to pump has to be established, the necessary documents should be filed with the proper authorities.

IRRIGATION WELLS DIFFER from those used to supply water for domestic purposes. Because of the large volume of water that has to be pumped from the well for irrigating even a small farm, special equipment is required to put down the wells. Heavy well-drilling rigs must be used.

The well screen (or the gravel pack, if required) has to be designed to fit that material in the water-bearing formation, so that the fine sand will be held back without causing excessive head losses, which increase the pumping lift. The well casing must be strong and durable and big enough to permit the installation of a pump of the required capacity. The well must be located where it will tap a good water-bearing formation, but it also should be located, if possible, where it will serve the entire area to be irrigated at the least expense for the distribution system.

The usual practice is to try to find a site for the well at or near the high point of the land to be irrigated; from it all the land could be served by gravity. The aquifer there might not be satisfactory, however. Exactly what the formation is cannot be determined without an investigation, and therefore test holes are drilled. If the holes show that the formation does not contain enough sand and gravel to produce a good well, other test wells are drilled.

When a location is found where the aquifer is suitable, the irrigation well is put down there. It may not be the most favorable location from the standpoint of irrigating the land, but that is less important than getting a good well.

Most irrigation wells are drilled in unconsolidated alluvial formations, and the rigs used to put down the wells are of the type adapted to drilling in soft materials. The mud-scow method is generally used in California. The mud scow is attached to a special drill rig with enough power to operate the equipment and to hoist the loaded scow to the surface. Because of its great weight, the mud scow can drill through layers of fairly hard rock.

Double stovepipe casing is used to line the hole. The casing is forced down with powerful hydraulic jacks as the drilling progresses. The wells so drilled are 12 to 16 inches in diameter and may be more than a thousand feet deep. After the well is drilled to the required depth, the casing is perforated opposite the water-bearing formations by ripping slots or punching holes with special perforating equipment. Thousands of successful wells have been drilled in California and elsewhere by this method.

Shallow wells up to 100 feet in depth and of small diameter can be put down with a sand bucket and any well-drilling rig with spudding equipment. For larger wells an orange-peel bucket is used to remove the material from the hole. Wells put down by these two methods are usually cased with lightweight galvanized pipe, made by rolling 16- to 12-gage sheets into a cylinder and then riveting the seams. The casing is forced down by levers or by loading the top of the casing with sand excavated from the hole. The casing is perforated before it is installed. That is done by punching holes or slots of the required size in the metal sheets before they are rolled into cylinders. This method can be used only in places where no rock strata are encountered.

Rotary rigs of the type used in drilling oil wells sometimes are used for putting down irrigation wells, but they are not well adapted for drilling

in unconsolidated material. They are effective in layers of hardpan, calcareous clay, sandstone, or similar sedimentary formations. The drilling is done by rotating a bit attached to a hollow drill stem, through which drilling mud is forced at high pressure. The mud rises to the surface on the outside of the drill stem and carries the drillings with it. The heavy rigs required are too expensive to move and install to justify their use for drilling shallow wells.

The reverse-circulation rotary method is effective in putting down large-diameter wells, not more than 200 feet deep, in unconsolidated material. The principle on which it operates is that the water used in drilling is drawn up through the hollow drill stem rather than being forced down through it, as in the standard rotary method. The material removed from the bottom of the well as the drilling progresses is carried to the surface by this stream of water. Because the water inside the drill stem is moving upward at a high velocity, it can carry out larger particles than the slow-moving upward flow of the water on the outside of the drill stem of the standard rotary rig.

The disadvantage of the standard rotary method in this respect becomes greater as the size of the hole increases, because the velocity of the stream varies inversely as the square of the diameter of the well.

When the reverse rotary method is used, the hole is kept filled with water to prevent caving. No casing is necessary while the well is being drilled. After the hole has been completed, casing is installed, which is smaller in diameter than the well bore. The intervening space is filled with selected gravel. The casing is perforated before it is installed in the well. The area to be perforated is based on the location of the water-bearing formation, as determined while the hole was being drilled.

Wells drilled by the reverse rotary method frequently produce larger yields for the same drawdown than those drilled by other methods. Part of the increase is due to the larger size of the wells, but the fact that the gravel pack can be more accurately placed in the well is probably a more important factor. Also, since drilling mud is not required to bring the excavated material to the surface, there is no danger of clogging the water-bearing formations with mud.

Another reason for the higher efficiency of the method is the speed with which holes can be put down. Under favorable conditions, 100 feet of hole can be drilled in 8 hours. Because of the rapid progress of the drilling, the aquifers are not disturbed as in other drilling methods, in which the jarring action of the bailer or standard tools compacts the material.

The cost of drilling irrigation wells varies with the diameter of the hole, the depth, the nature of the formation, the diameter and thickness of the casing, and the type of well screen and gravel envelope. The cost of a 36-inch well with 18-inch sheet-metal casing is 15 to 20 dollars a foot when drilled by the reverse rotary method. That includes the gravel pack. Test holes in alluvial formations, which are usually drilled by the standard rotary method, cost 50 cents to a dollar a foot. No casing is required. Drilling in rock is more expensive.

More accurate samples of the underlying formations can be obtained if the test hole is drilled with a sand bucket. It is more expensive, because the hole has to be cased and because progress is slow, but if any question exists as to the suitability of the formations, this method should be used.

DEVELOPING THE WELL is necessary to obtain its maximum capacity for a given drawdown. The developing process removes the fine material from the formation near the well screen, thereby opening up the passages so that the water can enter the well more freely. The process, properly done, can increase the capacity of the well up to 50 percent.

The customary method of developing a well is by means of a surge block, which is pumped up and down opposite the water-bearing sand with the drill rig. Another method is to use the test pump. Alternately starting and stopping the pump will produce a surging action, which washes out the fine material from the formation. Airlift pumps sometimes are used for developing wells.

Dry ice also is used. It is dumped into the well in chunks. Its rapid change into gas in the water causes a violent disturbance, which washes out the fine material. Sometimes the well is capped when dry ice is used—a procedure that builds up pressure in the well and forces water out through the screen. Releasing the pressure by opening a valve in the cap causes the water to flow back into the well. This reverse flow washes the fine material out of the formation into the well. After the surging is completed by any of these methods, the fine material remaining in the bottom of the well is removed with a sand bucket. All these methods produce satisfactory results if the work is done properly. The well should always be developed by an experienced driller, however, because improper methods may ruin the well.

A CAPACITY TEST should be made on every irrigation well before the pump is bought, because the pump must be accurately fitted to the well in order to obtain a plant with the maximum efficiency. The test should determine the water level before pumping starts and the drawdown at several discharge rates. The maximum rate tested should approximate the rate at which the pump is to be operated. The discharge at each pumping rate should be measured with an acceptable measuring device, such as a weir, end orifice, Parshall flume, or Pitot tube. The well should be pumped at each rate until the drawdown becomes fairly constant. If the drawdown continues to increase very much after several hours of pumping, it is an indication that the capacity of the well is being exceeded. The increased drawdown may be due to the clogging of the gravel pack or screen with sand or to the failure of the formation to give water readily. Sometimes it is due to the small size of the ground water reservoir.

The well test is usually made by the driller, because his rig is on the site and he can install the test pump without bringing in more equipment. Most drillers own a test pump. The use of a new pump for the purpose is not recommended, because most new wells pump some sand, which wears the impellers and may ruin the bearings. Thus the efficiency of the pump is reduced—a serious matter if the pump to be permanently installed in the well were used for the tests. Because the test pump is used only for short periods, high efficiency is not important.

THE HYDRAULICS of water wells—that is, the theory of flow of water from the water-bearing formation into the well under different conditions—is not fully understood. But some principles, which are helpful in designing irrigation wells, have been established.

The capacity of a well is proportional to the permeability of the water-bearing sand. It is approximately proportional to the thickness of the formation as well as to the drawdown. The capacity increases as the diameter of the well increases, but at a much slower rate. It decreases as the area influenced by pumping the well increases. The effect of the area of influence is small.

Increasing the diameter of the well should increase the discharge only slightly, but actually there are advantages in choosing a large-diameter well. The velocity of the water through the sand and gravel surrounding the well is less, and the danger of washing sand into the well is reduced. An adequate number of perforations can be made in the screen without weakening it very much, because the screen can be made larger. There is less danger of clogging a large screen having ade-

quate perforations. Also the possibility is smaller that deposits of chemicals from the water will form on the screen or in the sand and gravel when the velocity of the water is small, because the pressure changes that cause the deposits are reduced. Pumps of large size, which have large capacities and high efficiencies and operate at low speed, can be installed in a large well.

The discharge of wells in artesian formations is directly proportional to the drawdown. In nonartesian formations, the rate of increase of the discharge with the drawdown varies. Three-quarters of the maximum discharge of the nonartesian well will be obtained when the drawdown is equal to one-half the depth of water in the well before pumping started. Increasing the drawdown from the halfway point to the bottom of the well will increase the discharge by only one-quarter of the capacity of the well. Therefore it usually is not feasible to draw down the well below the mid-depth of the water.

To obtain the maximum flow from a given water-bearing formation, the well should be drilled to the bottom of the formation. If the well is drilled halfway through, the yield for a given drawdown will be one-half the capacity of the formation. Increasing the depth of penetration of the formation is one of the best ways to increase the capacity of a well.

When wells that tap the same formation are drilled too closely together, they interfere with each other, and the capacity of each well is reduced. If the wells are more than a thousand feet apart, the interference usually will not be serious.

Small-capacity wells, such as used in batteries, where the water-bearing sand is only a few feet thick, may be drilled closer together. They usually are spaced 50 to 100 feet apart, but sometimes smaller spacings are used. When a battery of wells is pumped, the capacity of each well may be reduced 10 to 20 percent by the interference. The smaller the spacing, the greater will be the reduction in capacity. Because of the interference in battery wells and the difficulty in pumping a series of wells with the same pump, better results often can be had by putting down widely spaced small wells, which are pumped independently.

Screens are installed in wells so that the water may flow into the well with the least interference and still keep sand from coming into the well. To do that, the screen should have an adequate area of openings. The size of the openings should be such that only the smaller particles of sand in the aquifer can pass through them.

The head loss through a screen 1 foot in diameter increases rapidly if the percentage of openings in the screen drops below 20 percent. Increasing the percentage of openings beyond 20 percent, however, does not lower the head loss. This limiting percentage remains constant regardless of the discharge and regardless of the size of the gravel in which the screen is installed. If the screen is larger or smaller than 1 foot in diameter, the limiting percentage remains the same, but a different length of screen is required.

Another characteristic of well screens is that most of the water enters the well through the screen opposite the inlet of the suction pipe of the pump. The suction pipe therefore should be perforated so as to distribute the inflow along its full length. Otherwise high velocities may occur in the sand opposite the suction inlet, and large quantities of sand may be drawn into the well.

Gravel envelopes are used with well screens to help hold back the sand in the water-bearing formation and to reduce the head loss. The gravel is screened to a size that will hold back the sand in the formation. The gravel should be of uniform size so that the porosity will be a maximum. The diameter of the gravel particles (50-percent size) should not be more than 5 or 6 times the 50-percent size of the

sand, if the gravel pack is to be effective in holding back the sand.

When this rule is used as the basis for choosing the gravel, the head loss will be small. If the pack-aquifer ratio is greater than 6, sand may be carried into the gravel, thereby reducing the pore space and increasing the head loss. Too small a pack-aquifer ratio also will increase the head loss. Most well drillers use overly coarse gravel for the gravel pack.

If the water-bearing sand is well graded (containing particles of a large range of sizes) no gravel envelope is required, because then developing the well will form a natural envelope.

When a gravel envelope is used, the perforations in the screen are designed to hold back the gravel and not the water-bearing sand. Large perforations, which reduce the head loss, are used. The width of the openings need be only slightly less than the diameter of the gravel particles.

The capacity of the pump depends on the number of acres to be irrigated, the crops to be grown, the diversity of the crops, the length of the growing season, the temperature, and rainfall.

The pump is designed to supply the deficiency between the water requirements of the crops and that provided from other sources, such as rainfall and sometimes streams or reservoirs. As the acreage to be irrigated increases, the capacity of the pump in gallons per minute required per acre lessens. That is because the crops are more diversified and do not all have to be irrigated at the same time. If the average temperature is high, crops need more water than those grown in a temperate climate, because the evaporation and transpiration rates are higher. When the growing season is long, the pump can be operated for a longer time to deliver the water needed. Small tracts require a pump capacity of 15 to 20 gallons per minute per acre under average conditions; small farms (80 acres), 10 to 15; and large farms (160 acres or more) 5 to 10.

Another factor to be considered in deciding the capacity of the pump is the supply available from the well, as shown by the well capacity test. If the crops need more water than the well can produce with a reasonable drawdown, the acreage to be irrigated will have to be reduced or another well may have to be drilled.

Several types of pumps are available for use in wells.

The horizontal centrifugal pump is the cheapest, but its use is limited to wells where the suction lift does not exceed 25 feet at sea level and less at higher altitudes. It must be primed before it will start pumping.

Piston pumps can be used for small flows and high lifts. They are no longer used extensively in wells for irrigation.

Most irrigation wells are equipped with deep-well turbine pumps. They start without priming. The three main types are the centrifugal, mixed-flow, and propeller pumps. The classification is based on the kind of impeller. The centrifugal type has a small capacity but will pump against maximum heads with high efficiency. The propeller type has a large capacity and high efficiency at low heads. It cannot be used for high heads. The mixed-flow type of turbine has an impeller that combines some of the characteristics of both the centrifugal and the propeller types. It has a fairly large capacity. It can be installed in wells with casing too small for the centrifugal type.

Deep-well turbines may be lubricated by oil or water. The instructions should be observed so that the pump will always be adequately lubricated.

Turbine pumps with submersible motors are available. All types of deep-well turbines will give long and efficient service when they are used under the proper conditions.

Each deep-well turbine pump is designed to operate at maximum efficiency at a definite head, discharge, and rate of rotation. If one of those interrelated factors is changed, the

other two are affected. If the conditions under which a pump is operating are different from those for which it was designed, the pump will continue to deliver water but at a lower efficiency. However, the efficiency can be improved by changing the speed and the diameter of the impeller or the type and (if the change in head is large) by adding one stage—an additional impeller. For small changes in speed of centrifugal-type pumps, the discharge is proportional to the speed, the head is proportional to the square of the speed, and the horsepower is proportional to the cube of the speed. The characteristics of mixed-flow and propeller pumps do not follow those rules.

The manufacturer has complete information on the characteristics of each type of pump he makes and can supply a pump that will fit the conditions at practically any well. To do that, the manufacturer must know how much water is required, the drawdown of the well at different discharges, the elevation of the land to be irrigated with reference to the static water level in the well, and the size and length of the pipeline, if one is required to carry the water to the high point of the land.

Pumps made by different manufacturers may fit the requirements of the pumping plant, but they may vary considerably in price and efficiency. Good pumps have efficiencies of 70 to 80 percent. The pump with the highest efficiency should be chosen if its price is reasonable. Whether the price is reasonable can be determined by computing how much the power bills will be reduced by the use of the most efficient pump.

Deep-well turbine and centrifugal pumps operate at their highest efficiencies, when the suction lift is a minimum. The bowls of a turbine pump therefore are installed so that the impeller will be submerged when the pump is running. The suction lift will also be reduced if the suction inlet is equipped with a strainer and a bell entrance. Foot valves, sometimes used on centrifugal pumps to prevent the water from running back into the well when the pump is shut off, increase the suction lift. Gate valves do not increase the suction if the valve is of the same size as the suction pipe and is kept fully open. The loss through the valve increases rapidly if it is less than one-half open.

Check valves, which are frequently installed in the discharge pipe of the pumps, may cause considerable resistance to the flow of water in the pipe, especially if the velocity is low. Pipe sizes should be big enough, because friction in pipes increases rapidly as the diameter decreases.

The power required to drive a pump depends on the discharge, the total head against which the water has to be pumped, and the efficiency. Expressed as a formula:

$$\text{Horsepower} = \frac{\text{gallons per minute} \times \text{total head}}{3{,}960 \times \text{efficiency}}$$

Total head is the difference in elevation between the water level in the well when the pump is operating, and the land to be irrigated, plus the friction loss in the pipeline, if one is used. The efficiency, as here used, is the product of the pump efficiency and the efficiency of the drive (belts or gears).

THE CHOICE OF POWER UNIT to drive the pump is usually restricted to electric motors and internal-combustion engines. Steam engines are seldom used because of the high cost of operation. Windmills do not provide sufficient power, except for small plants, such as used to irrigate gardens.

Electric motors are dependable and economical to operate. They give long and trouble-free service. They are practically automatic. Electric motors of the type used for pumping plants operate on alternating current and run at a constant speed. Most motors are made to run at 1,760 revolutions a minute, but motors with speeds of 3,475, 1,160, and 870 revolutions a

minute are also to be had. Motor-driven pumps usually are connected directly and are designed to operate efficiently at one of those speeds. If the pump has to run at a different speed to fit the conditions, a belt or gear drive must be provided with the proper pulley or gear ratio to produce the required speed.

Electric motors can be designed to operate in a horizontal or vertical position. The vertical motors are especially effective for use on deep-well turbine pumps because the motor can be connected directly to the pump—the motor and the pump head making a single compact unit. Electric motors will operate satisfactorily with a continuous overload of up to 10 percent and at a higher overload for short periods. Pumping plants should be designed so that the motor is at least fully loaded, because it improves the efficiency of the plant and reduces the demand charge for power.

Internal-combustion engines are used to drive pumping plants if electric current is not available or is too expensive. The three common types of internal-combustion engines are gasoline, diesel, and butane. Gasoline and butane engines operate on the same principle. A mixture of gas and air is ignited by an electric spark. They use volatile fuels such as gasoline or butane and sometimes natural gas.

Diesel engines use heavy fuels such as distillate. The mixture of distillate and air is ignited by the heat caused by compression of the mixture in the cylinders of the engine. These engines will give dependable service, but they require more attention than electric motors.

Gasoline engines, with slight changes, can be made to operate on butane or natural gas. They run at high speed, and, since the horsepower produced is directly proportional to the speed, the weight of the engine for the horsepower produced can be kept low. The cost of gasoline engines per horsepower therefore is relatively small.

Diesel engines have a much higher compression ratio than gasoline engines and consequently must be made stronger. They do not operate satisfactorily at high speeds. Therefore a diesel engine is usually larger and heavier than the gasoline engine of equivalent horsepower. It is also considerably more expensive, but the high first cost is counterbalanced by the higher efficiency of the diesel engine and the low cost of the fuel. Diesels are harder to start than gasoline engines, and an auxiliary source of power, such as a large storage battery, compressed air, or a small gasoline engine, is needed to start them.

Internal-combustion engines, when used as power units, are made to drive a shaft in a horizontal position. They can be connected directly to horizontal centrifugal pumps, but for deep-well turbine pumps that have a vertical shaft a gear or belt drive must be used. Highly efficient gear and belt drives are available for the purpose. Because the speed of internal-combustion engines can be varied through a considerable range, without seriously reducing the efficiency of the engine, the speed can be adjusted so as to make the pump operate at maximum efficiency even though the conditions that the pump was originally designed to fit may have changed. They are more flexible than electric motors in that respect. Internal-combustion engines wear out quickly when loaded beyond their rated horsepower.

PIPELINES must be provided for pumping plants if the water has to be delivered to a point higher than the place where the well is located. Steel, concrete, vitrified clay, or composition pipe (such as transite or plastic) may be used.

Steel pipe is useful on high-pressure lines. It resists shocks, such as those caused by starting the pump or by the sudden closing of a valve. Deflection of steel pipe caused by settling of the soil under the pipe will not crack the pipe or cause leakage. Steel pipe is made in many sizes and weights suitable for any

discharge or pressure that might be required for the pumping plant. Such pipe is expensive, however, and rusts rapidly unless it is galvanized or coated with a durable paint, such as coal-tar or enamel.

Concrete pipe is used extensively for pump discharge lines. It is best suited for conditions where the pressure is low and the danger of shock is small. It is relatively cheap and is durable except in soils containing a high percentage of salts. Concrete pipe is brittle. It will break if the foundation settles or if it is subjected to heaving caused by frost action. Temperature changes and sudden wetting of the pipe may crack it. The pipe therefore is usually laid in the spring or fall and is kept wet while it is being installed. A surge pipe or air chamber must be installed near the pump to reduce the danger of sudden shocks.

Vitrified clay pipe, commonly known as sewer tile, is highly resistant to corrosion. It is not affected by moisture or changes in temperature, but it is brittle and must be protected from shocks by a surge pipe or air chamber if used in a pipeline for a pumping plant. Sewer tile is made in short lengths with bell and spigot joints. The joints are usually sealed with concrete, but a flexible sealing compound is recommended if any danger exists of settlement or heaving. The tile should not be used if the pressure will exceed 10 feet of water unless it is installed under competent engineering supervision.

Special pipes, such as those of transite and plastic, are sometimes used for discharge lines of pumping plants. Before one of these special pipes is chosen, its advantages and disadvantages should be investigated.

The resistance to the flow of water in a pipe depends on the amount pumped, the roughness of the pipe, and the diameter. Tables are available that show the feet of head required to drive various quantities of water through steel, concrete, and vitrified clay pipes of different diameters. This friction head must be added to the difference in elevation between the water level in the well and the land where the water is discharged in computing the horsepower required to operate a pumping plant. If the pipeline is long, the friction head may be the major portion of the total head against which the pump has to operate. Care in design of the pipeline is therefore important.

Because the friction head for a given discharge varies inversely as the fifth power of the diameter of the pipe, the proper size of pipe should be chosen. Furthermore, the additional cost of the pipe as the size increases and the friction head decreases has to be balanced against the saving in the cost of pumping. An engineer should be consulted to be sure that the most economical size is chosen.

THE COST OF PUMPING consists of the fixed charges (interest, depreciation, and taxes) and the operating costs (power, repairs, lubricants, and attendance).

The fixed charges must be paid whether the pump is operated or not. Operating costs are directly proportional to the total quantity pumped or the hours of operation each season. If the pump is operated for only a short period, the fixed charges will be the major item in the cost, and since the total quantity pumped will be small, the cost per acre-foot of water per foot of lift may be excessive. The lowest unit costs will be obtained if the plant operates for a long period each season. For such plants the cost of power is the major item of expense.

A modern plant, operated 1,000 hours or more a season, should pump water at a total cost of about 5 cents per acre-foot per foot of lift. If the plant is old and inefficient or if the plant is run for only a short period each season, the total cost may be doubled.

Pumping plants for well irrigation are expensive. They may cost between 5,000 and 10,000 dollars—sometimes much more if the lift is high and the capacity is large. Such equipment deserves good care. Neglect of the plant

may cause failure at the critical time when water is most needed for the crops. Water applied after the critical time will be largely ineffective. For maximum yield of high-quality crops, the water must be applied when it is needed most.

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Pumping Ground Water So As To Avoid Overdraft

Dean C. Muckel

To conserve ground water does not mean to hoard it or to stop using it. It means proper use within the limitations of the known supply and its replenishment.

Overdrafts or shortages of ground water have developed in the United States, although many places have a surplus.

The overdrafts that have become critical usually are due to the uncontrolled use of ground water. The rapid growth of cities and industries and in the West the vast development of pump irrigation account for most of the overdrafts. Often they are local and are caused by concentrated pumping within an area that may or may not cover a ground-water basin or reservoir.

Indications of overdraft may be seen in one part of a ground-water basin while a surplus exists in another part of the same basin.

An overdraft exists when the extractions from the whole ground-water basin exceed the safe yield of ground water.

Two concepts of safe ground-water yield are:

First, the quantity concept applies primarily to free ground-water reservoirs, in which the water table represents the upper surface of the reservoir. Changes in the volume of storage are indicated by a rise and fall of the water table.

Second, the rate concept applies chiefly to artesian ground-water reservoirs, which exist when the ground water is confined under such pressure that relief at some point will cause the water to rise above the bottom of the confining stratum—although not necessarily above the ground surface. Because they impound quantities of water, they are termed reservoirs, but they function as large conduits that transmit water. Changes in storage are small, and recharge usually occurs in areas remote from the locations where discharge occurs. The rise and fall of water in wells penetrating such a reservoir represent primarily changes in pressure, rather than changes in the volume of storage. The yield of artesian reservoirs therefore depends more on the rate at which water moves through the conduit, or aquifer, than on the amount of change in storage.

The rate concept in free ground-water reservoirs usually is secondary to the quantity concept, although water-bearing formations must supply water at (or nearly at) any desired rate of production.

Net safe yield of ground-water reser-

voirs is equal to the annual net draft over a long period that does not or will not exceed the annual recharge; lower the water levels (or pressure) in a series of dry years to the degree that economic pumping lifts are exceeded; or exceed a quantity that would cause a deterioration in the quality of the ground water.

THE WATER TABLE (or pressure surface, in the case of an artesian reservoir) in practically all the reservoirs falls during dry periods and rises when there is more rain; alternating downward and upward trends continue over periods of several years. Outflow originating in the ground water of each basin varies with the elevation of the water table in the reservoir. A single or shorttime record of the distance to water level (or pressure surface) is no more indicative of the normal or longtime conditions than the precipitation record for a single year is indicative of the average or normal precipitation of a given area.

Whenever average extractions by pumping during a cycle exceed the net recharge—the difference between supply to the ground water and the outflow from it—water is drawn from storage, the water table falls, and outflow decreases, and net recharge increases correspondingly. In the succeeding cycle, if extractions continue at the same rate, the difference between net recharge and extractions and consequently the net drop in the elevation of the water table will be lessened. The relationship between water-table elevation and outflow in some reservoirs is such that a balance between net supply and present extractions can be attained within a reasonable period. In others, the progressive drop in the elevation must continue through many cycles. In still other reservoirs, where outflow is relatively small, the balance may be brought about only through a reduction of extractions.

Outflow consists of one or all of the following items: Evaporation and consumptive use from lands of high water table, surface streams discharging out of the area, and underflow.

When pumping from wells is started, it must be accompanied by a drop in water level (or pressure, in the case of confined aquifers). The drop increases the opportunity for recharge from influent streams. It reduces the area of seep lands and uneconomic losses through consumptive use and evaporation. It provides opportunity for penetration of rain falling on the valley floors, which under normal conditions did not happen because of the groundwater levels were too high. It also increases the opportunity for underflow into the reservoir by increasing the gradient.

Extractions by pumping from wells at this stage of the ground-water development functions as a conservation measure by converting uneconomical losses to beneficial uses. Lowering of the water table also creates a capacity for storing and carrying over the water that originates in wet periods for use during dry periods.

In that respect a ground-water reservoir is not unlike a surface reservoir. A reservoir that is maintained full or nearly full at all times is not being used to greatest advantage. Falling water tables during dry periods should not necessarily be viewed with alarm, because water placed in storage during wet periods is being drawn upon and storage capacity is being created for the wet periods that follow. Falling or even static water tables create a serious problem when they exist during wet periods and the reservoir is not being fully replenished to start into another dry period. An overdraft for the reservoir is then indicated.

Individual pumpers may have different opinions as to whether an overdraft exists.

The user who pumps in a region where the water table fluctuates widely or is far below ground surface may think that any added extraction that increases either fluctuation or pumping lift is an overdraft.

Another pumper, located near the point of outflow of a ground-water reservoir where both fluctuation and lift are small, may consider that lowering the water table results only in reducing the outflow or the amount of water that otherwise would be wasted.

An extreme view is that of the pumper who is in a position to extract economically the last water in a reservoir and who considers that no overdraft exists as long as he can pump what he needs, no matter how many others are forced to go elsewhere or go without.

All the users need to know how and where ground water occurs and moves so they can develop and utilize the supply to the best advantage.

Subsurface water occurs in the interstices—pores or chinks—of the rock between the surface of the ground and the lower limits of porous, water-bearing rock formations. That interval has two zones. The upper zone is the zone of aeration. The lower zone is a zone of saturation.

In a discussion relating to wells and their behavior the concern is with the zone of saturation where the interstices are completely filled with water. When the upper surface of the zone of saturation—the water table—is under atmospheric pressure, it is free to rise and fall with changes in volume of stored water. Water found under those conditions is called free or unconfined ground water. If the upper surface of this zone is under hydrostatic pressure because of an overlying impermeable formation, the water is termed confined ground water, or artesian water. The elevation of the water table is indicated by the water level in a well penetrating the zone of saturation. When a well penetrates a body of confined ground water, however, the water will rise in the well to a height that corresponds to the hydrostatic pressure under which the water is confined. An imaginary surface that coincides everywhere with points to which this confined ground water will rise is called a piezometric surface.

Fluctuations in elevation of a water table indicate changes in the volume of storage of free ground water. Fluctuations in elevation of a piezometric surface indicate essentially changes in pressure within the body of confined ground water.

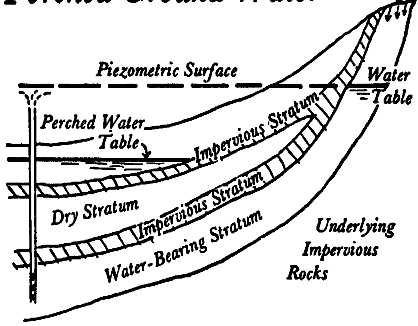
The main zone of saturation is overlain in places by unsaturated material that contains an impervious formation, above which a local zone of saturation may occur. Ground water in such a zone is termed "perched water," and its upper surface is a perched water table.

The movement and behavior of ground water depend largely on the size, number, shape, and distribution of interstices, or voids, in the rock formation of the earth. The rate of movement is directly proportional to the hydraulic gradient. Materials with a fairly uniform distribution of interstices include gravel, sand, silt, till, and similar unconsolidated deposits, together with sandstone, conglomerate, and other consolidated rocks. Those with nonuniform distribution of interstices include granite, gneiss, most limestones and basalts, and other massive rocks. The water-bearing characteristics of material having uniformly distributed interstices may be fairly well determined from laboratory or field examination of relatively small samples of the material, but the physical characteristics of massive rocks vary so greatly, even in the same formation, that predictions as to water available from them may be uncertain.

Porosity is the ratio of the total volume of interstices in a given mass of material to the total volume of such mass expressed as a percentage. The porosity of a given mass of material depends chiefly on the shape, arrangement, and degree of the assortment of its constituent particles; the extent to which cementation has taken place; the degree of compaction to which it has been subjected; and the amount of fracturing that has occurred.

Grain size itself has no effect on porosity. The size of grains in gravel, sand, silt, and clay varies greatly, but

Occurrence of Artesian and Perched Ground Water



the average porosity of well assorted samples of those materials may not.

Irregularity in shape of particles in granular material usually will increase its porosity over that of a material which has similar distribution of grain sizes but which is composed of more rounded and regularly shaped grains.

The degree of assortment of grains or the variations in their size has even greater effect on porosity. In a material in which the grains range in size from large rocks or boulders to sand and silt, the interstices between the larger rocks are occupied by the smaller particles, and the space between those particles is occupied by still smaller ones. In nature, granular materials seldom approach uniformity of size. Even in sands that are considered to be uniform, the largest particles may be much bigger than the smallest.

Porosity determines the amount of water a rock or material will hold. It does not determine the amount it will yield. Some of the water is retained by molecular attraction in the interstices as thin films surrounding the smaller particles of rock and in the minute interstices within and between granular particles or in very small joints of fractures. In material with small interstices, most of the water may be held by molecular attraction. Some clays have high porosities but will yield little or no water. Material with large interstices may have high water-yielding properties even though the porosity is slight. Coarse-grained sediments having particles of uniform size yield relatively large amounts of water.

Clean gravel is probably the most productive water-bearing material in the United States from the standpoint of yield, if cavernous limestone and lava are excepted. In clean gravel, broken and unweathered lava rocks, or limestone with large solution openings, the proportion of water yielded by gravity may approach the total porosity of the material. Coarse and well sorted sand will also yield an amount of water equal to a large proportion of its porosity. Fine sands yield less. Clays having very fine particles may yield no water. It is frequently and wrongly assumed that the water-bearing medium is satisfactory for wells simply because it contains many boulders the size of baseballs or larger.

If there were no fine particles, the boulders would be an indication of excellent material from which to extract water. Generally, however, the spaces around them are completely filled with graded sand, and the boulders therefore obstruct the flow, since they take up space and no water can move through them.

The specific yield of a material is the ratio of the volume of water which (after the material is saturated) will drain out by gravity to the total volume of such material. The specific retention of a material is the ratio, expressed as a percentage, of the volume of water which (after the material is saturated) will be retained by it against the force of gravity, to the total volume of such material. Specific yield plus specific retention is equal to porosity. Specific yield is useful in determining from water level changes the quantities of water extracted or necessary to recharge a ground-water reservoir. For instance, if a ground-water reservoir has a surface area of 10 square miles and an average specific yield of 7.5 percent has been determined, each 1-foot rise or fall in water level over the area represents 480 acre-feet of water change.

PERMEABILITY, perhaps the most important physical property of a water-bearing material, is the characteristic of porous material that allows it to transmit water. A large amount of laboratory research and field study of permeability has produced numerous formulas and procedures to determine the permeability of water-bearing materials.

One of the earliest experimenters was the French scientist Darcy. In 1856 he stated a rule: "The flow of water through a column of soil is proportional to the difference in pressure at the ends of the column and inversely proportional to the length of the column." Known as Darcy's Law, it remains the basic law governing the flow of ground water.

It is expressed mathematically as $V=\frac{kH}{L}$, in which V is the velocity, H the difference in head between two points in the path of movement; L the distance along the path of movement; H/L the hydraulic gradient, and k a constant depending in each instance on the characteristics of the material through which the water flows (particularly the size and arrangement of the particles of granular material or the size and character of the surface of joints, fractures, or solution openings) and may change with any change in these characteristics.

When water moves through large masses of material in the zone of saturation, the factor H/L becomes the slope of the water table or piezometric surface (hydraulic gradient). Frequently it is more desirable to determine the quantity of flow rather than the velocity, and Darcy's Law may be more conveniently stated as $Q=PIA$ in which Q is the quantity of water discharged in a unit of time; P is the coefficient of permeability of the material; I is the hydraulic gradient; and A is the cross-sectional area through which the water flows.

THE RATE OF MOVEMENT of ground water usually is very slow. Hydraulic gradients of more than 10 to 20 feet a mile are seldom encountered under natural conditions. Through formations in which wells of good yield may be developed, velocities of the order of 5 feet a day are usual. Velocities of 30 to 60 feet a day have been observed in the laboratory in well-assorted gravel with hydraulic gradients of 5 to 10 feet a mile. Field tests to determine underflow have shown velocities as high as 400 feet a day.

The standard coefficient of permeability of a material, as used by the Geological Survey, is defined as the rate of flow of water in gallons a day at 60° F. through a cross-sectional area of 1 square foot under a hydraulic gradient of 100 percent. Values of the standard coefficient of permeability, as determined in the laboratory, range from 0.0002 to about 90,000, but in ordinary water-bearing materials in which wells are developed they usually range between 10 and 5,000.

C. F. Tolman, in his book, *Ground Water*, gives the following average velocities of granular materials in feet a day:

Type of material	*Grain size, millimeters*	*Average velocity, 1 percent gradient*
Silt, sand, and loess	0.005 to 0.25	0.065
Sandstone and medium sand	0.25 to 0.5	1.16
Coarse sand and sandy gravel	0.50 to 2.0	6.33
Gravel	2.0 to 10.0	30.00

THE DISCHARGE OF A WELL is related directly to the permeability of the material that the well penetrates. When it is put down into a layer of water-bearing material and pumped, the water in the casing is first lowered, and the water from the saturated material surrounding the casing flows into the well. If pumping is continued, the water in the well will continue to lower, and the water coming from the saturated material will increase until it will equal the discharge. The water moving toward the well has to pass through the pores in the material, and

the closer it gets to the well the faster it has to move because the area through which it has to travel is decreasing continuously.

Because the velocity of water flowing through a water-bearing medium is directly proportional to the slope of the water surface, the slope increases as the water approaches the well, and the change in the slope is directly proportional to the change in velocity. The water surface formed as the result of the continuously increasing downward slope toward the well is an inverted bell-shaped depression, which is known as the cone of depression. The base of this cone theoretically extends outward from the well to the limits of the aquifer.

Measurable lowering of the water table has been encountered at distances of 8 to 10 miles where heavy pumping is carried on. At usual rates of pumping, the lowering is relatively small at distances exceeding 1,000 feet. The area under which a drop in water level occurs is called the area of influence. The distance that the water level is lowered by pumping is the drawdown; that is, distance between the water level in the well when being pumped and the static water level or water table.

A term commonly used in evaluating a well in relation to drawdown is specific capacity. It denotes the discharge usually in gallons per minute per foot of drawdown. In some localities the term specific capacity of the formation is used; it is expressed as discharge in gallons per minute per foot of drawdown per square foot of strainer or perforated area in the well casing.

Mathematical formulas have been developed to show the relationship between discharge of a well, shape and extent of the cone of depression, and characteristics of the material in which the well is drilled. Most of the formulas are based on assumptions that the material in which the well is drilled is homogenous in character; the well passes entirely through the aquifer or water-yielding material; and the well receives water throughout its entire length of penetration—conditions that are seldom if ever met in nature. The formulas, however, show certain fundamental relationships that are of value in studying wells.

In wells where the casing penetrates the full depth of the water-bearing stratum, the capacity of the well is directly proportional to the thickness of the stratum if the drawdown and other conditions remain the same. Also, the deeper the well is driven into a water-bearing stratum the greater will be the discharge for a given drawdown.

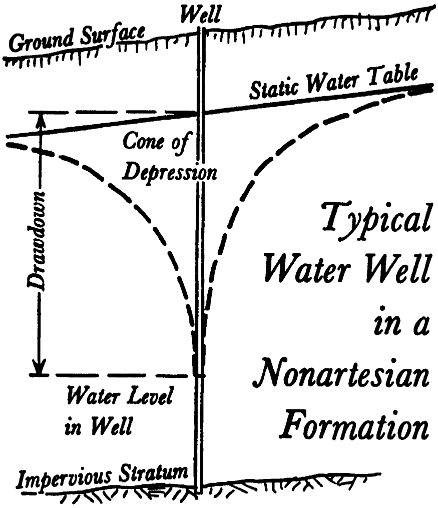
Where the wells penetrate deep into any water-bearing formations of considerable thickness, their capacity is directly proportional to the drawdown as long as the latter is small in comparison with the depth of the water in the well. If the drawdown is large, the discharge of the well does not increase so rapidly as the drawdown increases.

If the depth of water in the well is small, the yield per foot of drawdown will decrease as the drawdown increases, because as the drawdown increases, the depth of material through which the water enters the well is shortened. In artesian wells, the yield is directly proportional to the drawdown as long as the drawdown is less than the artesian pressure.

The formulas also indicate that the discharge from wells increases with increase in diameter but not in direct proportion. Theoretically, the discharge from a 2-foot well, assuming that the radius of influence is 1,000 feet and the drawdown is constant, is only 10 percent greater than from a 1-foot well, and the discharge from a 4-foot well is only 21 percent greater than that from a 1-foot well.

Usually where depth of the water-yielding formations is sufficient, no attempt is made to increase the discharge of a well by increasing its diameter; rather, the well is driven deeper and the size determined by what is

required to accommodate the size of pump to be installed.



Typical Water Well in a Nonartesian Formation

In shallow, water-yielding formations where deepening the well would not penetrate additional formations from which water could be extracted, an increase in diameter is advantageous. Often, where shallow water tables exist and the water-yielding formation is relatively thin, dug wells of diameters as much as 10 feet or more are used. Large discharges are not usually obtained but are often sufficient to irrigate several acres of land. Batteries of wells connected to a common pump also are used under those conditions.

When wells are spaced close enough to each other so that their cones of depression overlap, interference of wells is created, and the discharges of all the wells are reduced. The amount of reduction depends on the diameter, depth, spacing, and number of wells and the drawdown and nature of the water-bearing material. Interference should be avoided if possible.

In practice, if a well is in operation and other wells are planned, it is advisable to sink test or observation wells radiating outward from the existing well. Measurements of depth to the water table taken before and during pumping of the existing well will help one determine the area of influence. (Information on the construction of wells is given in Department of Agriculture Circular 546, *Putting Down and Developing Wells for Irrigation*, by Carl Rohwer.)

WHAT CAN BE DONE to avoid overdrafts? The question is not a simple one to answer.

Basically, if the entire ground-water reservoir is considered, the extractions by pumping must not exceed the net safe yield. The determination of the net safe yield requires extensive study and consequently usually is not undertaken until an overdraft already exists. Pumping within the area of most ground-water reservoirs is carried on to supply water for a variety of users—industries, municipalities, and, particularly in the West, irrigators—and all are in competition for it.

Concentration of wells has caused deep holes in the water table and in places has even reversed the normal direction of the underflow. These deep holes in the water table are actually great cones of depression; so much water has been extracted that a general lowering of the water table over many miles has resulted and the annual rate of replenishment cannot equal the extractions. Such conditions require reservoir-wide action to obtain outside supplemental supplies, limitation of pumping, or rearrangement of well spacing within the reservoir.

The basic hydrologic equation of a ground-water reservoir is: Recharge equals discharge.

Where pumping occurs, the draft must be, over a long period, at the expense of natural discharge, and the equation can then be written: Recharge equals natural discharge plus artificial discharge.

When, over a long period, natural plus artificial discharge exceeds recharge, the excess is supplied from accumulated storage and a condition of overdraft exists.

Obviously the only solution is to

increase the recharge side of the equation or reduce the discharge side to bring about a balance.

The recharge (or supply) items are: Surface inflow, subsurface inflow, precipitation on the area, and imported water and sewage.

The discharge (or disposal) items are: Surface outflow, subsurface outflow, consumptive use in area, and exported water and sewage.

Increase of recharge may be accomplished by importing water to the area either for direct consumption to relieve the pumping draft or for artifically recharging the ground-water reservoir, as through water spreading or injection of water into wells.

Decrease in the discharge side of the equation may be accomplished by eliminating consumptive use and evaporation losses from uneconomic plants and swamp or waste areas.

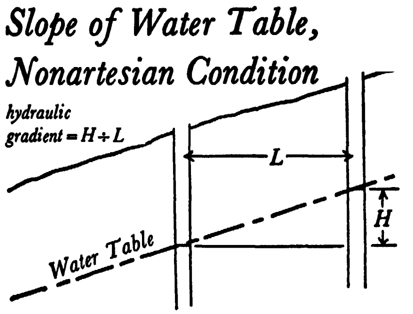
Areas of high ground water, such as may be found at the outlet of some ground-water reservoirs, tend to waste water. This waste can be eliminated by removal of vegetation or by lowering the water level through drainage.

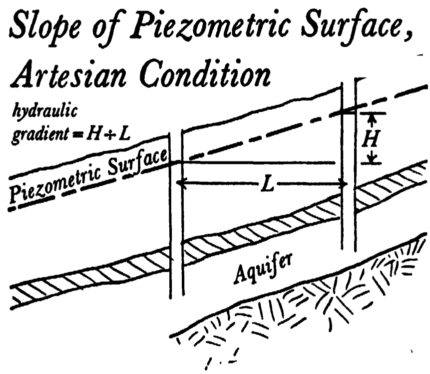
If drainage is used in this sense, the drainage effluent must be put to beneficial use. All water conservation practices within the area will also serve to reduce the natural discharge.

Preventing runoff, and thereby inducing deep percolation of precipitation, helps to bring the recharge and discharge into balance. Also, proper use of water in irrigation reduces evaporation and transpiration losses.

In artesian areas, water can be conserved by sealing wells and eliminating leaks from wells in which casings have failed. Leaking wells are known to be responsible for considerable loss of ground water—so much so that several States have passed laws making it illegal to allow an artesian well to flow wastefully or a leaking well to remain in use.

THERE IS NOW a general trend toward the planned utilization of the ground-water reservoirs. That will require





competent investigation and plans for ground-water development of the common supply of interconnected surface and ground waters. Enabling legislation usually is required. When a reservoir is operated under a planned program, the full use of the water will be obtained and no permanent overdrafts should be expected.

That appears to be the only way to avoid the results of the haphazard exploitation of ground water that has occurred in many areas. Any program proposed for developing a ground-water reservoir must of course meet the test of economic feasibility.

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Replenishing Ground Water by Spreading

Dean C. Muckel and Leonard Schiff

When we have overdrawn our ground-water account, how can we deposit some more?

The natural way is by seepage from streams, the deep penetration of rain and snowmelt into the ground, and the percolation of water from hills and mountains.

But they are not enough to replenish ground water in places where a great deal of ground water is pumped out and in places where surface reservoirs reduce the amount of water that seeps into the ground from natural stream channels, or channels in towns are realined and paved, or storm sewers, buildings, and pavements keep water from entering the ground. When that happens, the amount of water withdrawn exceeds the amount entering the underground reservoirs. An overdraft exists or is threatened. Water tables go down. Pumping costs go up.

A way to make new deposits is to build water-spreading systems, which spread the water diverted to them in times of excess runoff over a larger area and thereby increase the amount of water entering the soil. (The term "water spreading" is commonly associated with all methods of replenishing ground water.)

The design and operation of a spreading system are somewhat like those of an irrigation system, except that water is encouraged to percolate rapidly to the underground basin instead of being held within the root zone of the irrigated crop.

Artificial recharge by spreading is necessary wherever the use of ground-water reservoirs—that is, reservoirs under the ground—is planned. Many ground-water reservoirs can hold far more than the largest artificial surface reservoir, yet few are fully utilized to store floodwaters. Holdover storage in ground-water reservoirs can be provided with little loss of water by evaporation. Few undeveloped economical surface reservoir sites remain in the West, and the utilization of underground storage is a planned development. The subject is therefore of great importance.

To make full use of the underground storage it may be necessary to pull down the water levels by operating appropriately spaced wells during dry periods in order to create a storage capacity to be filled during later periods of surplus. Ground-water reservoirs, like surface reservoirs, are not utilized to best advantage if they are always kept full or nearly full. They should be depleted during dry periods to provide storage capacity for wet periods.

THE SOURCES OF WATER for recharging are rivers and canals that carry water produced directly by rainfall and snowmelt or released from surface storage.

Spreading usually is done during seasons of low irrigation demand, and therefore the facilities of storage and distribution can be utilized as an aid to spreading water without conflicting with irrigation. Sewage and industrial effluents may also provide additional sources of water. In areas of water shortage where large amounts of sewage are discharged to the ocean, the overdraft of water may be relieved by spreading reclaimed sewage. Pollution of the ground-water supplies by effluents must be avoided, however.

SPREADING METHODS ARE the basin method, the furrow method, the flooding method, and the use of pits, shafts, and wells. Each has its own advantages and disadvantages and (except the last) is widely used. The methods often are combined. Sometimes all four are used at once.

The topography, general slope of the land, amount of land available, condition of the water (clear or silty),

and characteristics of streamflow are factors to be considered in the choice of methods.

The basin method consists of impounding water in a series of small basins formed by dikes or banks. The basins are arranged so that the entire area may be submerged during spreading operations. The dikes often follow the contour lines of the ground surface and have outflow facilities so that excess water from the one basin will escape into the next lower basin. The outflow may overtop the dike or pass through it in pipes. Both methods are successful, and the choice between them depends on the material available for constructing the dikes.

The overtopping method requires a dike of a nonerosive material. The sausage dam, used very widely in southern California, consists of walls of rocks of various sizes bound together with heavy hog wire to form a rock mattress. Such a dam is seldom higher than 8 feet and is not considered economical unless the rock is near at hand. Protection should be provided at the toe of the dam to prevent erosion due to the force of the overflow.

The height of the outflow above the ground surface is adjusted so that, when the basin is full and water is escaping, the water will have backed up to the toe of the dike that forms the lower boundary of the next higher basin. Thereby the entire ground surface between the dikes is submerged.

The basin method is used in places where the ground surface is irregular and spotted with shallow gullies and ridges. The basins prevent the water from collecting in the gullies and running off before it has a chance to penetrate into the soil. Spreading by basins is not recommended if the water carries much silt or foreign material, which seal the surface of the spreading area and finally destroy the usefulness of the basins. One advantage of the basin method is that it wets a greater net area than any other method does.

The furrow, or ditch, method consists of sending water through a series of furrows or ditches somewhat like an irrigation system. The ditches are shallow, flat bottomed, and spaced close together so as to expose the maximum infiltrating area. Slopes of ditches usually are designed so that the velocity of the water will carry in suspension or as rolling bedload the silt and fine material that is detrimental to infiltration.

The ditch system usually follows one of three general plans:

1. Parallel spreading laterals extend at right angles from a main diversion canal. Pipes or open cuts through the bank of the main diversion canal provide entrance to the laterals. Gates are installed at each entrance to control the amount of water entering each furrow. The laterals generally are 3 to 12 feet wide. The depth of laterals is great enough to provide a uniform slope through ridges and depressions and thus to create a fairly uniform velocity.

For each series of laterals in the system, a reception ditch usually is provided. This ditch in the lower part collects the excess water from the spreading laterals. Water may then be redistributed in a new series of laterals or may be diverted back into the main stream channel if the limits of the spreading area have been reached. If enough water is available, this system is recommended for streams carrying considerable silt, the theory being that the silt will be carried through the spreading system and back into the main stream channel, where periodic floods may move it to the sea.

2. Instead of diverting from the main canal to a series of small laterals, the main canal may be divided into two separate ditches. These two may then be divided into four smaller ditches. Division is continued until the flow in the ditches dwindles to trickles and finally disappears. At each division point, drop gates are provided to control the water entering each series of ditches.

3. By the contour ditch system, the water is spread through one ditch that

follows the contour of the ground surface. As the ditch comes to the limits of the area provided for spreading, a sharp switchback is made. Thus the ditch is made to meander back and forth across the land, gradually approaching the lower part of the spreading area.

The flooding method consists of passing water slowly over the land surface in a thin sheet. Good results have been obtained with it. It is adapted to areas of gentle slopes where the topography is not cut by large gullies and ridges. Few such areas exist, however, and often some construction is required to prevent the water from collecting in small streams and running off without spreading over the required land surface. Small ditches or embankments may be constructed to divert the water from the shallow gullies to the higher ridges, where it may spread in all directions and wet the slopes of the ridges as it again runs to the lower levels. By the generous use of these training ditches or embankments, all or a large part of the area may be wetted.

Water may enter the uppermost point of the spreading area in a main canal and then be released to follow the gullies and the training structures. Usually, however, one main ditch or perhaps several meandering over the highest ridges or circling the upper boundary are desirable. From these ditches the water may be diverted at intervals. This method gives better control of the water; if a training wall or ditch fails, only a part of the spreading operation need be interrupted to make repairs.

The highest rate of water movement into the soil occurs in places on which the native vegetation and soil covering have been least disturbed. On a properly designed flooding system, little if any of the spreading area need be disturbed.

If the ground surface is too irregular to use the flooding method, basins or furrows may be used to confine the water to a definite area. The cost of preparing the land for flood spreading is much less than that for any of the other methods, and the rate of water movement into the soil is higher.

In the flooding method the water is less easily confined than in the other methods. Suitable structures, such as embankments or ditches at the boundaries of the spreading area, are often necessary to prevent damage to nearby lands by escaping streams of uncontrolled water. In this system, as in others, the water should be under perfect control at all the diversion points and at the entrance to the spreading grounds.

It is hard to design a complete flooding system before the water is applied. The main ditches, the diversion works, and the control device should be installed first. Then, when the water is applied, the smaller training walls and ditches can be located and constructed to the best advantage. It is advisable to have at least one man on the grounds during spreading. The ditches and embankments should be patrolled and inspected. Often such simple adjustments as the placing of a few shovelfuls of dirt in the proper place will divert enough water to wet several additional acres. Thus a well-developed spreading system may be made highly efficient at a low operating cost.

Spreading water in stream channels is also classified as flooding. If the stream has a wide bottom, caused by the meandering of the channel, a low dam or weir may be extended across the bed. The water, in passing over the weir, spreads out in a thin sheet over the entire streambed and thereby increases the wetted area. Due precaution should be taken to avoid creating a hazard in time of flood by backing up the water or diverting it out of its normal streambed. There are few if any operation costs in this type of spreading other than for a periodic inspection of the dam or weir.

Water diverted into pits, shafts, or wells does not follow strictly the definition of water spreading, but it serves the same purpose and is therefore referred to as a method of spreading.

It is not used extensively because of its high cost and other limitations. Abandoned gravel pits, old wells, or other existing holes are generally used.

Shafts or pits are seldom sunk primarily for the purpose. Sometimes wells that are normally pumped during the growing season are used for recharge during other seasons. High rates of flow into the well are usually obtained, but a comparatively small amount of water is sunk in this manner because of the limited area involved. Water supplied to the pits or wells should be free of silt to prevent sealing of the bottoms and sides. It is extremely costly sometimes to rid wells or shafts of silt deposits.

Usually the use of wells or shafts is confined to specialized conditions. They may be used where impermeable strata or layers occur between the surface and the water table, a condition that renders replenishment by surface spreading unfeasible. Also they may have some merit where land values are too high to set aside enough area for surface spreading.

Successes as well as failures have been reported with this method. Generally best results have been obtained by using chlorinated water free from silt and by maintaining the well casing constantly full so as to prevent undue fluctuation and turbulence of the injected water. Chlorination is necessary in some places to prevent the growth of soil-clogging micro-organisms. The advantage of head, or water pressure, is of course obtained with this method. In places where water has been injected into the wells under pressure, special construction has been necessary to prevent the upward movement of water around the outside of the casing. For recharge wells in alluvium, the gravel-packed type appears to be best.

Selection of spreading sites must be made with a knowledge of the geologic structure of the ground-water basin so as to obtain the most efficient utilization of the storage capacity and of the transmissibility of the aquifers. That is necessary to be sure that the water spread and put underground will reach the zone intended to be replenished. Selection also should be made with respect to surface texture and subsurface structure of the soil in order to obtain the most rapid rates of water movement into and through the soil. When those two requirements are fulfilled, a more defined choice of area can be made on the basis of values of land, ease of delivering water, topography, and other factors.

Water-spreading systems in the early days of artificial recharge were located on pervious debris cones at the mouths of canyons, because the conditions were ideally adapted for spreading. The water was close at hand, and temporary diversions were simple to construct. The debris cones lay at a higher elevation than the valley floors, and any water put underground would eventually reach the main body of ground water, where pumping from wells was greatest. The debris cones were generally considered wastelands. Thus the size or value of the area devoted to spreading was not a major concern. The problem was one of diversion and protection from flood flows that periodically poured from the canyons.

A general increase in ground-water development for irrigation has created need for artificial replenishment in areas not particularly adapted to spreading. Often the location of already established wells confines the spreading area to soils of low permeability. Water enters and moves through agricultural soils much more slowly than it does through debris cones. The high valuation of agricultural soils makes it desirable to limit the size of spreading areas. As a result, experimentation and research were begun to design and operate systems that would be effective under unfavorable conditions.

Soils of low permeability are usually medium- or fine-textured, ranging from sandy loams to clay loams. The

infiltration rate—the rate at which water flowing or impounded at a shallow depth can enter the soil—may be satisfactory or unsatisfactory. Even a satisfactory infiltration rate may be short-lived, however, because of the clogging effect of biological secretions, particularly during prolonged submergence. Many soils are troublesome because hardpan or stratified layers, or other nearly impervious layers, exist in the profile at shallow depths.

Frequently the percolation rate—the rate of downward flow through a depth of soil—through the hardpan soils is less than the infiltration rate. Hardpan or clay layers beneath small spreading ponds have little effect on the infiltration rate because water may readily flow laterally over such layers. On a large spreading area, however, water is confined largely to vertical flow downward except near the boundaries. The rate of flow of water thus confined is limited to the percolation rate of the less pervious layers under the surface. Thus their effect on reducing the infiltration rate increases as the size of the area increases. But the greater the depth to the less pervious layers, whether the pond is large or small, the greater the opportunity for lateral flow.

Soil and water treatments and operation or management procedures to increase the infiltration rate have been studied on small test ponds (14.7 feet square) near Bakersfield, Calif., since 1936. The Department of Agriculture completed a laboratory in Bakersfield in 1949 to study the hydraulics, soil physics, and soil microbiology involved in water spreading. The laboratory work is concurrent with present water spreading on experimental ponds and large areas. The Kern County Land Company, the North Kern Water Storage District, the California State Division of Water Resources, the California Agricultural Experiment Station, and the Department of Agriculture cooperate in the studies.

Treatments to increase infiltration and percolation rates are designed to enlarge soil pores, improve aggregation, stabilize aggregates, and establish continuity of pores through the surface soil or through lower, less pervious layers, or both. Involved are dispersion, slaking, and swelling of soil particles; leaching and deposition of material; biological and chemical activity; and compaction, which tends to clog pore space.

The average infiltration rate for Hesperia sandy loam and Exeter sandy loam, untreated during a prolonged flooding, is about 0.9 foot a day for a small test pond and 0.5 foot a day on large spreading areas. Infiltration rates are lower on large areas than on small, handworked test ponds because of the smaller proportions of lateral flow and because of the removal of topsoil, breakdown of soil structure, and compaction due to land leveling and soil manipulation by heavy equipment.

Average infiltration rates of 1.5 feet a day on large spreading areas for a spreading period that may last up to 9 months would be satisfactory. Higher rates are desirable.

The S-shaped infiltration curve generally obtained has been explained as follows: The first drop is due to swelling and dispersion; the following increase accompanies the removal of entrapped air; and the final decrease is due to gases, liquids, and solids secreted by micro-organisms in the soil. Initial infiltration rates are recovered and the infiltration curve repeats itself after the soil has dried to the permanent wilting point. Infiltration rates for Hesperia sandy loam (underlain by shallow, discontinuous, stratified layers) are slightly higher than for Exeter sandy loam (underlain by shallow, discontinuous hardpan).

Vegetative treatments have produced outstanding increases in infiltration rates on Hesperia sandy loam and Exeter sandy loam. Runs on decomposed trash from cotton gins, incorporated in the soil on small test

ponds, have always been high in infiltration rate, with maxmium rates of 12 feet, declining to 5 feet a day in 200 days, as compared to 3.6 feet, declining to 0.3 foot a day for untreated soil. The trash is applied as a 2- to 6-inch layer and then incorporated in the soil. Infiltration rates immediately following the application of the trash or other organic matter are low because of biological secretions resulting from the processes of decomposition. The secretions, upon drying, form a rather stable coating around soil particles and improve soil aggregation. Better entrance conditions are established with a more stable interface at the soil surface, and a surface soil medium, which seems to create a good transition into the untreated soil below. It is also possible that the coatings around soil particles offer less resistance to flow than untreated soil. The beneficial effect of cotton-gin trash has been continuous over the observed 6-year period.

Cotton-gin trash incorporated in the soil and deep chiseling increased the infiltration rates on a few acres of a large spreading area where the soil was compacted originally by land leveling. The average infiltration rate was raised from 0.3 foot to more than 1.0 foot a day—a decided improvement. Infiltration rates of more than 2.0 feet a day are probably unattainable unless the limiting effect of the shallow, subsurface, less pervious layers can be reduced.

Runs on well established Bermuda-grass on small test ponds have always shown high infiltration rates; maximum rates were 11.6, declining to 5.4 feet a day in 200 days, compared to 3.6 feet, declining to 0.3 foot a day, for untreated soil. The beneficial effect of Bermuda-grass has been continuous over a 5-year period. This grass will stand partial submergence. At one time it survived a dry period lasting 13 months.

Other early treatments, such as gypsum, calcium chloride, detergents, removal of crusts, and removal of topsoil, were all considerably less beneficial than either cotton-gin trash or Bermuda-grass.

Soil conditioning chemicals have been tested to increase recharge rates. Conditioner A (partial calcium salt of vinyl acetate-maleic acid) was incorporated 0.1 percent by weight to 3 inches of dry surface soil in a small test pond. The soil was then wet to a depth of 3 inches and dried. The maximum infiltration rate of 11 feet per day achieved with conditioner A during the first run was 2 times the highest rate of the same pond before treatment. The final infiltration rate of 3 feet a day after 320 days of submergence was 6 times the rate of the same pond before treatment for a like period of submergence. The second run, following drying to about the permanent wilting point, produced infiltration rates slightly less than the first run.

Samples brought into the laboratory from soil treated with conditioner A showed definite improvement in aggregation, compared with samples taken from just below the treated depths. Conditioner A appears to form a network of clay particles within which soil particles of various sizes are bound into aggregates. It may be applied in larger amounts to achieve good aggregation as the soil becomes coarser in texture. The treated soil probably prevents clogging that would normally occur at the surface and also provides a good transition for water to move into the soil below.

Conditioner B (ammonium lignin sulfonate and wood sugars) was incorporated 0.5 percent by weight to 3 inches of dry surface soil in a small test pond. The crust produced during the initial wetting and drying of conditioner B was broken gently and the soil wet and dried again. Unnecessary soil manipulation will cause a detrimental breakdown in aggregation. The maximum infiltration rate of 9.6 feet a day obtained with conditioner B during the first run was 3.5 times the highest rate of the same pond before

the treatment. The infiltration rate dropped below the practical limit of 1.5 feet a day in 3 months. That rate is about twice the rate after 3 months of submergence of the same pond before treatment. The rapid decline in infiltration rate during the first run was attributed to the further decompositions of the wood sugars in conditioner B. Infiltration rates during a second run were about twice those of a similar run on the same pond before treatment.

Conditioner C (ferric ammonium organic complex) was incorporated 0.4 percent by weight to 3 inches of dry surface soil in a small test pond. After the initial wetting and drying, the soil was again spaded, wet, and dried. Conditioner C did not increase infiltration rates over those obtained on the pond previous to treatment. We have reports, however, that conditioner C is effective on soils of higher clay content than found in the Bakersfield area.

THE SELECTION OF A TREATMENT, whether vegetative or chemical, depends upon local soil conditions, the cost of obtaining and applying the materials, and the possible benefits. Unlike vegetative treatments, some chemicals are effective on the first run.

Future experiments will determine whether a single application of a chemical will be beneficial for as long a period of time as vegetative treatments. The hauling, distribution, and incorporation of cotton-gin trash are costly. Grasses may provide additional benefits as a hay or forage crop. Effective and economical methods of distributing material in the soil are sought, particularly when applying small amounts of chemicals to large areas. Consideration should be given to the application of chemicals in solution and the use of carriers for dry chemicals.

Other materials were tested. Pumice, a natural gray or white rock ejected by volcanoes and frothed by gases, did not increase the maximum infiltration rate but it did tend to sustain a higher than normal rate after the peak. The large volumes of air within the pores of pumice may prolong aerobic activity, at least during the early stage of wetting. Such material may also prevent some normal movement of soil particles. Mixtures of conditioner A and pumice have been suggested.

WATER TREATMENTS may become the most economical way to increase the infiltration rate. Gypsum (calcium sulphate) increases the infiltration rate where high percentages of sodium tend to disperse soil. Present detergents appear to have little effect on infiltration rate over a prolonged period.

New types of detergents and detergents combined with other treatments are possibilities. Germicides may be used in some cases to prevent biological clogging. Wetting agents and chemicals may possibly be leached down to eliminate the clogging material in less pervious boggings. Thought is being given to liquids that contain enzymes. A single-application treatment of water that promotes soil aggregation and develops large pores in the soil for some time would be ideal.

SUBSURFACE SOIL TREATMENTS to open or penetrate less pervious soil horizons are ripping, drilling backfilled shafts and wells, and constructing ditches.

Ripping shallow, discontinuous hardpans underlying Exeter sandy loam doubled the average infiltration rate of untreated soil. Shafts 4 feet in diameter and 20 feet deep, backfilled with gravel, were drilled through less pervious material to reach and apply high water pressure to coarse soil or soil of high permeability. The maximum injection rate through such a shaft was 0.52 acre-foot a day, which is equivalent to the average rate of spreading on 1 acre of untreated soil. The injection rate dropped with time because of clogging.

Sand filters used on the top of shafts removed materials carried by water and prevented the formation of algae

on the gravel pack. Small pea gravel was mounded over some of the gravel shafts to simplify filtering. The resistance due to algae growths on the sand filter or on top of the pea gravel reduced the depth of water in the gravel pack and lowered the rate of flow. The rate of flow increases when such growths are removed. The movement of live or dead algae or other material into the gravel pack must be prevented. Experiments have been started on shafts in contact with greater amounts of coarse material. Simple filters and practical methods of cleaning filters are sought. The use of chlorine to prevent biological activity, although expensive, is warranted in a few instances.

Ditches up to 1,000 feet long, 10 feet deep, and 10 feet wide at the bottom with sloping sides were constructed on three spreading areas. The ditches cut through less pervious material and touched varying amounts of coarse material. One ditch on Exeter sandy loam operated at 2.5 acre-feet an acre a day during the initial run. Loose, small particles of soil on the entire surface of the ditch were not stabilized by vegetative or chemical treatments, except in a few small sections treated with conditioner A. Rates of water movement into the soil, measured through infiltrometers or 12-inch diameter tubes, were 2 and 3 times greater on the conditioner A-treated than on the untreated sections. The large pores were clogged by the movement of the loose, small particles of soil on the untreated sections. Water elevations in piezometers (0.5-inch pipes), jetted below the bottom of the ditch from 1 foot to 40 feet, showed high losses in water pressure through the surface of the soil due to clogging. Water elevation changes showed a perched table rising toward the bottom of the ditch. The water table, perched on a deep stratum, did not rise high enough in the 2 months of spreading in the ditch and vicinity to interfere with the movement of water from the ditch into the soil.

Water spreading in Cucamonga Canyon, San Bernardino County, California. Cross walls of rock, bound together by heavy hog wire, spread the water over the entire bed and thereby create the maximum infiltrating area.

The ditch on Hesperia sandy loam was in contact with the largest amount of coarse material and operated at a rate of about 6 acre-feet a day. The rate declined when the water table, perched on less pervious material about 30 feet below the surface, rose to the bottom of the ditch in less than 2 months. This perched water table was fed by the ditch and by water spread on surrounding areas. The inlet is in the lowest part of the ditch, and water was initially brought in at a rate which filled the ditch slowly. That prevented much of the movement of the soil particles. Coarse soil has less tendency than fine soil to move and clog, but even a coarse soil will clog in time if fed by water that contains small soil particles. Scraping to remove clogged soil may become necessary.

Operational or management procedures, such as variation of the amounts, depths, and location of soil treatments; methods of manipulating the soil; methods of initially wetting or incubating the soil; duration of wetting and drying periods; size, shape, and spacing of spreading areas; and surface head are as important as soil and water treatments in creating high infiltration rates. For example, besides some procedures already mentioned, the highest percolation rates were obtained in the laboratory with the soil

tubes receiving the longest period of incubation. The percolation rate was highest for soil tubes given intermittent rather than continuous flooding during the incubation period. Apparently intermittent flooding promotes aerobic conditions, which may be beneficial.

Surface head—the depth of water on the soil surface—directly affects the infiltration rate. Infiltration rates increased directly proportional to total head in infiltrometers and small ponds on untreated soils. The total head consists of the surface head plus the length of saturated soil column. The surface head appears to be a large part of the total head on untreated soils that have been partially clogged.

Soil treatments and operational procedures to increase infiltration rates appear warranted when such rates are initially less or tend to become less than the percolation rate of relatively shallow, subsurface soil horizons. As treatments are used to increase percolation rates, treatments to obtain corresponding increases in infiltration rates become desirable. Increases in infiltration rate above the percolation rate, however, appear warranted in two cases:

First, when such increases will result in a longer saturated column on a thin layer of less pervious material. This longer column will exert greater pressure and force more water through the less pervious material in a given period.

Second, when such increases will result in a greater depth of water on less pervious horizons and appreciable lateral flow can occur. The proportion of lateral flow to vertical flow increases as the area gets smaller. A good arrangement for maximum lateral flow would appear to be long, relatively narrow strips. Areas between spreading strips may be farmed or used for alternate spreading areas. Alternate spreading areas could be used in a rotational system, whereby some strips are flooded while others are being dried for recovery in infiltration rate. In a rotational system, areas would be flooded only while infiltration rates are relatively high, since infiltration rates decline with time during submergence. Gases produced by microorganisms in the soil as they break down organic matter, which tends to retard infiltration rates, would be released more frequently in a rotational system of spreading. A low infiltration rate over a long period of time is conducive to the development of anaerobic conditions and the production of gases that are not as readily soluble as gases produced under aerobic conditions. Thus it may be possible to put more water into the soil in a rotational system of spreading on parts of a large area than by flooding the entire area. It may be possible to spread water on treated strips of a large area, farming between strips, and put as much water into the soil as by flooding the entire area. A "subsurface lake" is visualized in this case.

The artificial replenishment of ground water will become more important as the use of ground water increases. The practice is already widespread in connection with replenishment for irrigation in the West, notably California. It is being used in municipal and industrial areas in the Midwest and East.

Each specific location requires individual study and exploration to cope with its peculiar conditions and only general principles can be set forth for all areas.

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Ways To Control Losses From Seepage

C. W. Lauritzen

Considering the importance of water, it is worth emphasizing again that about one-third of all water diverted for irrigation is lost in conveying it to the land and that another third percolates too deeply or runs off during the process of application to the land. Some loss is a legitimate accessory to use, but losses of this order cannot long be tolerated.

The major part of loss in conveyance can be attributed to seepage, which can largely be eliminated by lining the irrigation canals. Other conveyance losses, such as operational wastes, can be reduced by better management.

Substantial losses due to seepage occur in storage. Those losses, like the losses in canals, can be controlled by lining the reservoirs. Lining of small overnight storage reservoirs to control seepage is a common practice. The lining of large reservoirs does not seem economical or practical at present but may well become feasible in the future.

The 1950 Census of Agriculture lists 19 percent, or 18.4 million acre-feet of water, as lost in conveyance. According to the Bureau of Reclamation, 37 percent of all the water diverted on 46 of its projects in 1946 was lost in conveyance—23 percent was attributed to seepage and 14 percent to operational waste.

Many factors influence seepage losses. The permeability, or water-transmitting capacity, of the earth material in which the reservoir or canal prism is located probably is the most important. Losses are greater when the water is conveyed long distances and are proportional to the wetted perimeter and hydraulic gradient, as influenced by the depth of the water in the canal.

Vegetation along canals and around reservoirs adds to the losses because the plants transpire water and often contribute indirectly by perforations left in the banks by plant roots. Rodents and insects likewise cause losses by their burrowing in embankments of canals and reservoirs. The position of the water table influences seepage where it intercepts the canal prism.

As to the management of canal systems: Even with the best management it is hard to regulate the flow at the head of a long canal so that the water the farmers need will be available without waste. Operational waste in most canal systems could be reduced considerably by providing equalizing reservoirs along the course of canals from which water could be withdrawn to supply local demands and to which excess deliveries could be diverted. Such reservoirs must be lined if they are in permeable material.

MEASUREMENTS are needed to estimate the amounts of water lost by seepage in order to adjust deliveries and line canals. Several methods have been employed for measuring seepage, but none is entirely satisfactory.

Inflow-outflow methods give reasonably accurate results for long lengths of canal and in sections subject to heavy losses. They consist of measuring the water that flows into a section of canal and the water that flows out of it. The flow may be measured by the standard methods of measuring streamflow—flumes, weirs, and current meters. The difference in the amount of water flowing in and flowing out is considered to be the conveyance loss. If diversion gates are tight, the difference is the loss due to seepage and evapotranspiration by plants.

The accuracy of the method is governed by the accuracy of the stream measurement at the beginning and the end of the section. If the losses are not great or the section is short, small errors in measurement may make the difference between a loss and a gain. This method has an advantage over other methods in that measurements can be made with least interference to

the delivery of water and at less cost than measurements by other methods. It is not accurate enough for isolating losses in short canal lengths, except when losses are extreme.

The ponding measurements are well adapted to the isolation of losses in short sections. They are made by installing a check or a dam at both ends of a section of canal, filling the section with water, and observing the rate at which the water seeps away. That rate can be measured by one of two methods—by measuring the water that must be added to maintain the water elevation in the section or by measuring the rate of recession of the water surface. The seepage rate is computed from the volume which this represents by the formula:

$$S=\frac{w(d_1-d_2)L}{PL}$$

In the formula, S is seepage (cubic feet per square foot per 24 hours); w is average width of water surface in feet; d_1 is depth of water in feet at beginning of measurement; d_2 is depth of water in feet after 24 hours; P is average wetted perimeter in feet; and L is length of canal section in feet.

The ponding method has two disadvantages. It prevents delivery of water during the time of measurement. It is costly. When measurements are made before and after the irrigation season, the problem arises of obtaining water to fill the sections. Losses as measured before the irrigation season and afterwards, when the water has been out of the canal for a time, may be quite different from losses that occur during the irrigation season. That has to be taken into account. Usually a series of measurements is made and the equilibrium value used. The seepage is assumed to be at equilibrium or in a steady state when the rate changes little between succeeding measurements.

The permeability of soil changes when water is applied and is lowered with time. The reduction in seepage with the time the water is in the canal reflects this general characteristic. If the water table near the canal builds up, that also will reduce further the seepage according to the time the water is in the canal.

Seepage meters and permeameters, of several similar types, have been developed to estimate the seepage from a canal without interfering with the flow. They consist of a cylinder or open-end chamber for confining a portion of the canal bed area and a metering device for measuring the water admitted to the confined area. Some of them are designed to operate at a constant head, others with a variable head.

The permeability of the material of the canal bed can be computed from this equation by assuming a value for the flow length: •

$$k=\frac{ql}{ah_f}$$

In the formula, q is the volume of flow in unit time, in cubic feet; l is flow length, in feet; h_f is loss of hydraulic head in feet; and a is confined area in square feet.

When a supply tank or tube in which the head varies is substituted for the plastic bag or other constant-head device, the permeability is computed as follows:

$$k=\frac{2.3al}{A} \quad \log_{10}\frac{h_1}{h_2}$$

In the formula, h_1 is hydraulic head at beginning in feet; h_2 is hydraulic head at the end of unit time in feet; A is area of canal bed confined, in square feet; a is cross-sectional area of supply tank in square feet; and l is flow length in feet.

Losses normally are expressed in cubic feet per square foot each 24 hours, or depth of water which seeps away per unit area in 24 hours. The use of the variable head seepage meter or permeameter is subject to the criticism that where the head on the confined area is greater than the depth of water in the canal, there may be movement from the confined area to

the area adjoining; and where the head in the reservoir is lower than the depth of water in the canal, there may be movement of water from the canal into the confined area.

A number of investigators have used seepage meters for evaluating losses. Variations between measurements have been great, even for meters installed side by side. It has not been established whether the differences represent actual differences in the permeability of the bed material or errors in measurement due to the performance of the equipment. Some investigators recognize the variability but believe that an estimate of seepage can be obtained by averaging a number of measurements and adjusting the result for the difference that has been observed to exist between measurements of this type and seepage losses measured simultaneously in the canal by the ponding method.

Measurements by seepage meters are usually made at the bottom of the canal because they cannot be satisfactorily installed on the side slope. This limitation further restricts the possibility of securing a good estimate of seepage losses from them, as seepage losses apparently are greater from the sides than from the bottom of canals.

The well permeameter, another device for estimating seepage losses, consists of a calibrated reservoir, which meters water to a well of a uniform diameter and a definite depth. The water in the well is maintained at a constant level, usually the designed operating level for the canal, by a float device. The seepage is computed from the amount of water withdrawn from the reservoir over the period of measurement.

One can compute the permeability of the soil from the measurements and, by making certain assumptions, can estimate the seepage from a canal in the location of the measurement. The conversion is based on a theoretical analysis, and the assumptions cannot be fully verified. It is difficult, however, to correlate permeameter measurements with seepage rates as determined by the ponding method.

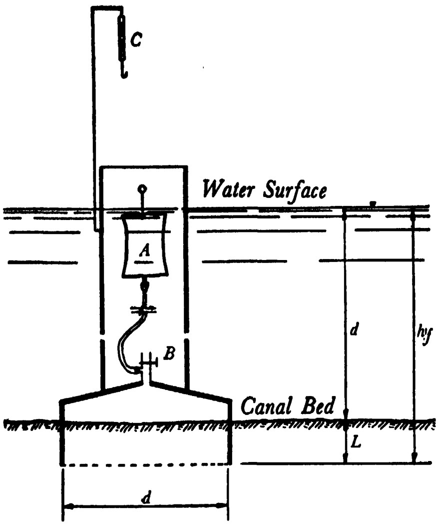
The permeability of material taken from the canal bed or along the course of a proposed canal is another way to estimate seepage losses. Good correlation has been obtained between the dry-pack permeability of samples of bed material obtained from ponded canal sections and the seepage measured from ponded sections. The data available is limited, but according to research findings at the Utah State Agricultural Experiment Station seepage from canal sections is approximately 0.15 the rate indicated by the dry-pack permeability. This general relationship does not hold for the sections in which gravel strata or fractured rock lenses contribute to seepage.

To determine the permeability by the dry-pack method, the soil is air-dried and passed through a 20-mesh screen, placed in the permeameter, and compacted in the dry condition by jarring the permeameters. A head of water is applied to the surface and the percolate collected. The rate of percolation will increase for a short time and then drop. Seepage losses are best estimated from the maximum rate because, after the maximum rate is reached, the rate decreases with time, the rate approaching some minimum value. The permeability or the flow that takes place through the soil under unit hydraulic gradient is computed from the equation:

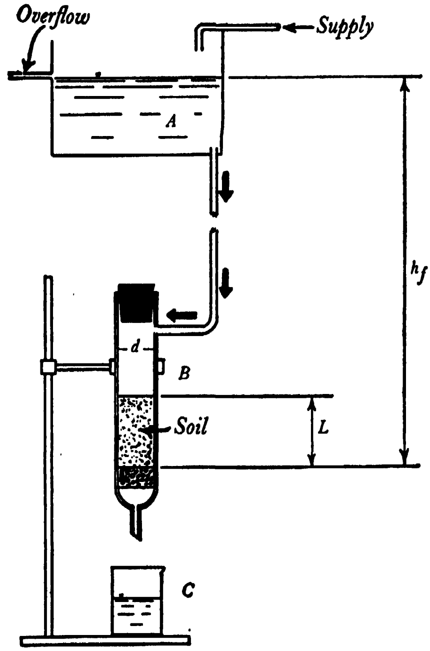
$$k=\frac{ql}{ah}$$

In the formula, k is permeability, q is quantity of percolate collected in unit time, l is the flow length, a is the cross-sectional area of the soil column perpendicular to the direction of flow, and h is the hydraulic head loss.

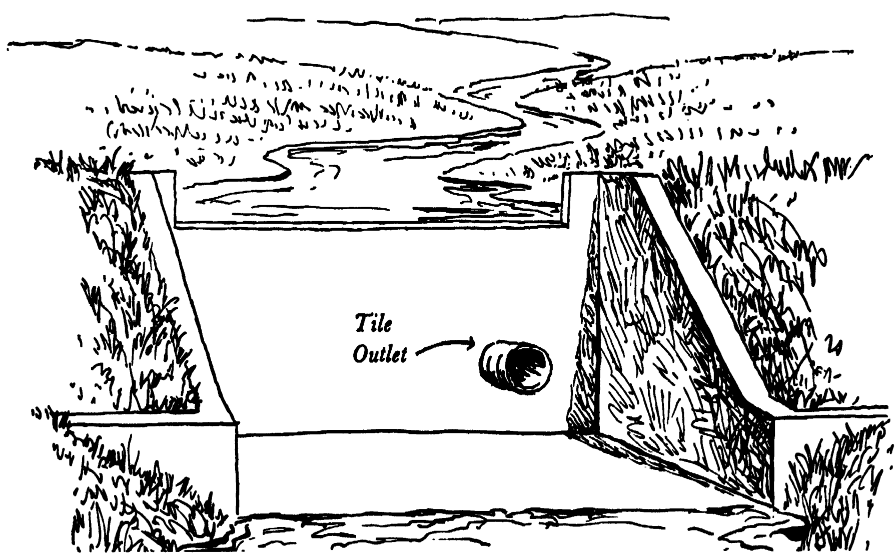
In view of the problems and the inaccuracy of the field methods for estimating seepage losses, it appears that the permeability of soil samples taken from the canal bed, or samples from the soil profile along the course of a proposed canal, offers one promising



This drawing shows a salinity laboratory seepage meter used for estimating seepage losses from irrigation canals. The lip of the seepage meter is inserted into the canal bed with valve B open. The flexible bag A is filled with canal water and connected through a tube to the meter. After the air has been exhausted from the tube, valve B is closed and bag A weighed with scale C. After a period of time the bag B is weighed again. The difference in weight represents the weight of water percolating through the canal bed confined by the meter. The loss may be expressed as depth of water per unit area or in terms of permeability by assuming a value for L. L is frequently assumed to be equal to the depth of penetration of the meter lip.



This drawing shows equipment for measuring the permeability of disturbed samples of earth material. The sample is placed in the permeameter tube B and a head of water applied from a constant head tank A. The permeability of the sample is computed from the equation $k = q \frac{l}{a h_f}$, in which k = permeability; q = quantity of percolate C collected in unit time; l = the flow length; a = the area of the soil column or $\pi \frac{d^2}{4}$ and h_f = the hydraulic head loss.



approach to estimating seepage losses.

One of the greatest difficulties is the conversion of permeability data to seepage losses. This necessitates information on the hydraulic gradient that causes ground-water flow away from canals and, in the absence of that information, involves assumptions regarding the position of ground water table and the nature of the subsurface material. This is particularly true when permeability measurements are used to estimate the seepage along the course of a canal yet to be constructed. Hydraulic gradients can be measured along the course of an operating canal by means of piezometers installed in the canal bed at the site of each sampling location. Piezometers are installed in sets to a succession of depth at about 3-inch intervals, the water level in the piezometers is measured, and the gradient is computed.

LINING is an effective way to control seepage losses in canals and reservoirs.

The first requirement of a lining is that it provide a barrier to the transmission of water. Further, it must be economically feasible—the annual cost, which includes initial costs prorated over the life of the lining, and the maintenance costs must not exceed the benefits.

The major function of a lining is to conserve water. It also protects the land from waterlogging and salinity. Depending on its type, a lining reduces the costs of maintaining canals, insures against interruption in water deliveries, and helps control weeds.

Many materials are used. Earth, concrete, and asphalt are the basic materials used in the United States. Wood and metal have been used somewhat for conveying water, particularly in flumes. Plastics may be useful for linings in canals and as tubing for conveying water.

EARTH MATERIALS vary in their water-transmitting properties. Some coarse-textured materials are a million times more permeable than fine-textured soils. Within limits and with some exceptions, permeability increases with the increase in the size of the particles of the material. The size distribution of the particles provides a general guide to the water-transmitting properties of soil, but it has been found that soil of the same texture may vary widely in permeability. A soil of coarser texture, such as sandy loam, may be less permeable than some clays. Because of the low permeability of the fine-textured earth materials, they have been used extensively as covers over the coarser materials to reduce seepage losses from reservoirs, canals, and ditches. Sometimes they have been in the form of thin toppings or blankets and at other times as sediment placed by the water. More recently a thick compacted-earth lining has come into use.

The linings referred to as thin toppings commonly are 1 inch to 1 foot thick. Sometimes they are placed on the surface with little preparation or protection. At other times the canal is shaped, the lining material is spread and rolled, and a topping of gravel is added for protection against erosion. Any of these applications will tend to reduce seepage losses, but haphazard applications usually do not justify their cost. The thin earth linings are reasonably effective when soil having low permeability, independent of compaction, is used and the lining is protected from erosion by a topping of gravel or other material. The linings should be at least three inches thick; four inches is better.

The permeability of earth can be varied widely by treatment. The permeability of most fine-textured soils can be lowered by compaction in a moist condition in the laboratory, but the low permeability induced by treatment is not permanent. Permeability tends to increase with use when soil is used for lining canals. Consequently only earth materials that have a low permeability, independent of compaction, will be effective in controlling seepage losses. They are rare; usually

they are low-grade bentonite deposits.

Of four types of bentonite, only the alkali bentonite, the type that expands upon wetting, is adapted to lining. High-grade bentonites—whose gel volume is 80 percent or more—may be mixed with coarser textured materials, such as sandy loams, at the rate of 10 to 20 percent to produce fairly satisfactory lining material. Usually high-grade commercial bentonite costs too much to be used for lining, but if bentonite deposits are nearby, soil-bentonite mixtures, or a straight bentonite blanket, covered with a layer of earth and topped with gravel, might well be used.

The most satisfactory test for estimating the effectiveness of an earth material for lining is to measure its permeability. Any material of lower permeability placed as a topping over material of higher permeability tends to reduce the seepage and therefore will have some value, but it is more practical to use only materials of low permeability. Arbitrarily, a permeability of 1 foot a year, or less, is suggested as the maximum permeability allowable in material to be used for thin linings.

SEDIMENTATION is another—but unsatisfactory—method of reducing seepage from canals with earth. Sedimentation is accomplished by mixing fine-textured earth materials, such as clays and bentonite, with the water in a canal and allowing them to settle out. It does not cut loss enough, and its effectiveness is temporary, because the sealing material is removed from the surface by scouring and the sealing effect is destroyed when it dries.

The control of seepage losses by this method has advantages if it could be made effective. Seepage could be controlled without removing the water from the canal, and the cost of the treatment should be low. Several materials have been investigated for use as sediment lining. Among them are commercial bentonites and fine-textured deposits of earth material.

A newer type of lining is the thick-compacted earth lining. It is constructed by rolling the material in 6-inch layers. The moisture content of the soil should be at the optimum for maximum compaction. The width of lining on the side slope is about 8 feet—the width required for the operation of standard construction equipment. If the lining is installed on a 2:1 side slope, the thickness of the lining would be about 3 feet. The thickness in the bottom is usually somewhat less than the thickness on the side slopes.

Seepage measurements immediately following construction on a section of canal lined with thick-compacted earth showed about the same losses as a similar section of canal lined with concrete. It is reported that the seepage losses on some thick-compacted rolled linings installed in Canada were satisfactory at first but have tended to become more permeable and started to leak heavily after several years of use. Some volume-weight measurements made on the linings indicate that the weight per unit volume has decreased with time, probably because of the action of frost and wetting and drying.

The success of thick-compacted earth linings depends on the use of satisfactory material. A wider range of materials perhaps can be used for this type than the thin types. Generally the most satisfactory materials for the thick-compacted linings are gravelly and sandy clays. If too much clay is present or if the clay is of the expansive type, cracking tends to develop and the lining tends to become unstable. These linings have been used with and without a protective cover, but covers surely add to the durability of the lining.

CONCRETE has been commonly used for lining canals. It is rather expensive, but it gives long, trouble-free service. The standard concrete lining used to consist of a 3- to 4-inch concrete slab reinforced with steel bars on 1-foot centers both ways. A survey of linings installed by the Bureau of Reclamation failed to prove, however, that the

use of reinforcing steel in concrete linings justified the additional cost. The current practice is to use unreinforced concrete except in places where a failure of a lining might damage something other than the lining itself, such as residential or industrial areas.

Concrete linings to be durable should be limited to sites with good drainage and nonexpansive soils. If that is done, concrete linings should give good service anywhere in the United States. The minimum thickness of concrete linings is a moot point, but a reasonable recommendation would be 3-inch unreinforced concrete in the North and 2-inch unreinforced concrete in the South.

Expansion joints need be used only where linings adjoin structures. Contraction joints should be constructed on 10- to 12-foot centers with 3-inch concrete, and 6- to 8-foot centers in 2-inch concrete linings. The contraction that accompanies the setting of concrete will then normally cause no cracks in the slab between the joints.

When the linings are installed in panels, the construction joints serve well for the contraction joints. Lining placed with slip forms and pavers can be grooved to a depth of about one-third the thickness of the slab to provide satisfactory contraction joints. Because of the weakness that the grooving induces at this point, the cracking will be localized along the grooves. The provision for joints (rather than allowing the cracking to occur where it will) permits sealing the joints and eliminates the chances that ragged cracks will become focal points for spalling.

The most satisfactory and the commonly used calking compound available in 1955 was a cold-applied, internal setup mastic, formulated from fiber and asphalt. It has some extensibility and bonds fairly well when it is applied to clean concrete surfaces. It deteriorates in time, however, and must be replaced periodically.

Concrete linings must be constructed from good concrete, properly mixed. A source of information is a pamphlet, *The Design and Control of Concrete Mixes*, published by the Portland Cement Association, Chicago, Ill. Another is the *Concrete Manual*, prepared by the Bureau of Reclamation and obtainable from the Superintendent of Documents, Washington 25, D. C.

The quality of concrete depends on the aggregate used and the strength of the cement paste. Only well-graded, sound aggregate should be used. The water-cement ratio should be kept as low as practical, with an eye to economy and proper consistency for satisfactory placement. It is wise to formulate a mix for each job and to maintain careful control of the mix during construction. To do that may be impractical without a laboratory and trained technicians, but a satisfactory mix can be made by following the instructions in the pamphlet of the Portland Cement Association.

The entrainment of 3 to 5 percent air in concrete adds greatly to the durability of exposed concrete surfaces. Cements can be bought that contain an air-entraining agent, or the agent may be purchased and added to the mixing water. The entrained air also improves the workability of the mix and permits the use of a lower water-cement ratio.

The shape of concrete linings may vary from semicircular to rectangular, but usually the linings are trapezoidal in shape, with side slopes ranging from 1 or 1.5 horizontal to 1 vertical. Semicircular and rectangular linings necessitate forming the concrete, which adds to the cost. It is usually not done unless special conditions—such as canals on steep hillsides—make the use of trapezoidal cross sections undesirable. If the concrete is hand placed, the side slopes should not be steeper than 1.5:1—which is about the limit of steepness if the fresh concrete is not to slump during screeding and finishing. Side slopes as steep as 1:1 can be used if linings are placed with slip forms and pavers. A concrete with about a 2-inch slump is usually most satisfactory for canal linings if unformed concrete is used.

Placing and finishing the concrete linings by hand are giving way to slip forms and pavers for placing linings. The use of machines to place concrete linings has lowered costs of the linings. There is opportunity for even greater mechanization, particularly for excavating and trimming small canals before placing the concrete. Nevertheless, the construction of concrete linings in panels with hand labor may still be the most economic method for lining small canals if farmers do the work themselves.

The cost of 3-inch unreinforced lining on a typical job was 2.62 dollars a square yard—88 cents for excavation and trimming, 72 cents for placing, and the rest for the concrete. The work was done mostly with farm labor. Concrete linings in larger canals often are installed with pavers.

SHOTCRETE is a form of concrete. It consists of portland cement and sand, applied pneumatically. It has been used extensively for linings, particularly in the South and for resurfacing old concrete and rock cuts. Except for very thin linings, it is more costly than slip-formed concrete linings.

Soil cement—soil stabilized with portland cement—has been used for lining a few test sections of canal but has not proved to be satisfactory for canal lining generally.

ASPHALT has been employed for lining canals. Cold mixes, like road mixes, and asphaltic concrete have been used. Hot mix, consisting of sand and gravel aggregate, with a binder of 50–60 penetration asphaltic cement, has given fairly satisfactory results. The mix consists of a blend of sand and gravel with a maximum of 0.75-inch aggregate and about 8 percent asphalt for binder. A mix should be formulated for each job. It is placed with a slip form or heated screed moved slowly along the canal by a winch or tractor. In the larger canals, asphaltic concrete linings might well be installed with pavers.

A new material is the buried asphaltic membrane, which consists of a layer of asphalt covered with a topping of fine-textured earth and a protective covering of gravel. In one type, an application of catalytically blown asphalt is applied directly to the subgrade. This asphalt has a softening point of 175° to 200° F. and is applied at a temperature of about 375°. It retains its flexibility over a wide range of temperatures without becoming fluid. It is tough and, properly applied, provides an effective barrier against seepage. The subgrade to which it is applied should be smooth and firm. If the subgrade is coarse textured, it should be covered with a cushion course of fine-textured material. Likewise, the first few inches of the cover material should be fine textured, and the topping should consist of material with a coarse enough texture to resist erosion.

The use of the buried asphaltic membrane lining is limited to canals having stream velocities of 3 feet a second or less. It requires a topping of gravel. The total depth of cover should not be less than 1 foot. The canal, before it is lined, must be overexcavated to allow for thickness of the lining. Normally that is not a serious problem because most earth canals when trimmed will have enough capacity if they had adequate capacity before lining. The buried asphaltic membrane lining can be installed quickly and at a low initial cost and under weather conditions that are unsuitable to concrete and earth construction. Satisfactory installations have been made over light snow covers and on soft wet subgrades when frozen so they would support the construction equipment.

Buried asphaltic membrane linings, that are properly installed with a cover retained in place, will give reasonably good service for at least 10 years. Because catalytically blown asphalt has a high softening point and must be applied hot, it has to be applied with special equipment and usually necessitates a contract job. The sprayed

type therefore is less well adapted to the lining of small canals or short sections of large canals than some other types. The asphalt is transported hot in railroad tank cars that hold 8,000 to 12,000 gallons or, for smaller jobs, in tank trucks. It has to be kept from solidifying in transit because liquifying it once it has set is costly.

Prefabricated liners — the second type—make it possible to use buried asphaltic membranes on smaller jobs. They come in rolls similar to asphalt roofing. The chief disadvantage is the large amount of labor needed to install them. The canal prism must be uniform in cross sections, and considerable care should be exercised in placing the lining if small gaps or wrinkles along the joints are to be avoided and the lining made watertight. Properly installed, the prefabricated types may give better service than the sprayed type as they will be freer of membrane imperfections and more resistant to the penetration of plant roots.

Asphaltic liners about one-half inch thick have been used as exposed liners in canals and reservoirs. Their use has not been extensive enough to prove their durability, but they provide effective seepage control. Their advantages over the buried type for canals are that a smaller lined perimeter is required and they can stand higher stream velocities.

PRELIMINARY INVESTIGATIONS of plastic film and synthetic rubber sheeting for use as exposed liners have not been entirely promising. It is almost impossible to install these thin membranes in a canal without some wrinkling, which is objectionable. Their thinness makes them subject to damage by livestock, farm equipment, and other hazards to which canal linings are subjected. Those objections are eliminated when the materials are used as buried linings, but then the linings have the characteristics of other types of buried linings. A ditch of larger cross section is required, velocities must be limited to about 3 feet a second, and a nonerosive cover material must be provided. The lightness of the materials makes it possible to handle them in larger units and with less labor. Wrinkles will not impair the effectiveness of the membrane as a barrier against percolating water and, as it is buried, will not affect the surface characteristics of the lining.

Butyl rubber resists deterioration due to exposure and biological activity and root penetration, a desirable property if a liner is to be durable.

THE COST OF LINING depends on management, site conditions, and the availability and cost of materials. A few figures for average jobs may be helpful. A 3-inch unreinforced concrete canal lining can be installed, including excavation and preparation of subgrade, for about 3 dollars a square yard. Buried asphaltic membrane linings normally cost about 1 dollar a square yard. Buried membrane linings constructed of such materials as polyethylene and polyvinyl chloride film may cost a little less than buried asphaltic membrane linings. Earth linings and buried membrane linings normally are cheaper, but that depends upon location and site conditions.

PIPES are the most efficient way to convey irrigation water and provide maximum control. In localities where a considerable head of water is available, as when water is brought from higher to lower elevations, pipelines generally are as economical as open canals. The use of pipes instead of open ditches in field-distribution systems has advantages: Land the ditches normally occupy can be tilled. Crossings, weeds, and ditch maintenance are eliminated. Seepage losses and labor requirements are reduced.

Pipelines used to consist primarily of concrete, steel, or wood stave pipe. Steel and concrete pipe are used extensively. Reinforced rubber-gasketed concrete pipe is commonly used in the main distribution systems. Unrein-

forced concrete pipe is used in low-pressure farm distribution systems.

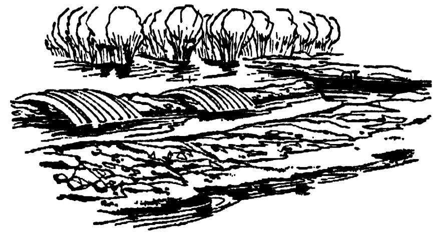
A newer development is the cast-in-place concrete pipe. It costs less.

Precast or monolithic pipe is unreinforced and designed for low-pressure heads, usually not exceeding 10 feet. The contractors usually guarantee it against leaks for 1 year. Wall thicknesses range from 2.5 inches for 24-inch pipe to 5 inches for 48-inch pipe. On one job in California, 48-inch pipe was constructed for the low cost of 5.15 dollars a linear foot and a production of 150 feet an hour was attained. The 36-inch size apparently is the most economical to construct. The 24-inch pipe is more costly per unit of capacity because of the restricted working space; the larger sizes cost more because they need a heavier framework. Six-bag concrete, with 1-inch maximum aggregate and equal parts of sand and gravel, is commonly used. A low water-cement ratio is maintained in order to secure early strength and facilitate finishing.

Another promising development for farm distribution systems is lay-flat flexible tubing, which reduces seepage and eliminates ditch maintenance and the problem of ditch crossings. It has more flexibility and can be moved from place to place. Tubing can be obtained with spile outlets spaced at convenient intervals for diverting water into irrigation furrows.

Among the materials used for flexible tubing are canvas and supported plastics. The supported-plastic tubings are easy to handle because they are light and remain dry on the outside. They are suitable for relatively high pressure systems if they have high strength-supporting materials.

Financial as well as technical problems limit the adoption of seepage-control measures. All canals would be lined and most of them lined with concrete if cost were not a factor. Farmers, if they could afford it, would have underground pipe distribution systems. But only about 5 percent of all irrigation canals were lined and a much smaller percentage of field laterals were lined in 1955. Considerable underground pipe has been put in use in



some areas, notably California. Extension of lining and wider use of underground pipe for farm distribution systems awaits the economic justification and the financial ability of water users to make the improvements.

The greatest retarding factor to lining of canals and laterals is the inability of the user to benefit by the saving of water. Under the law in 1955, a user with adequate water rights stands to gain little by expending money for lining because he could not use the water saved for irrigation of additional land or be reimbursed in any way for the financial outlay for the lining. In fact, it might be that lining would jeopardize his right because of the nonuse of the part of his water saved by a more efficient conveyance and distribution system.

Extensive lining programs are likely to be deferred except in places where the water supply is inadequate or where seepage is damaging land next to canals. The situation presents a problem: Saving water is in the interests of all the people, and some action should be taken to that end.

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Irrigation Water and Saline and Alkali Soils

Milton Fireman and H. E. Hayward

If irrigation water is of good quality, the soils to which it is applied may be improved because of the calcium in the water and the beneficial effect derived from leaching or washing any excess salts from the soils. But if the quality of water is unsatisfactory, the soil may deteriorate until it will no longer produce satisfactory crops.

Four major characteristics determine quality of water for irrigation: The total concentration of soluble salts; the concentration of sodium and the proportion of sodium to calcium plus magnesium; the concentration of bicarbonate; and the occurrence of the minor elements, such as boron, in amounts that are toxic.

The total concentration of soluble salts is an essential consideration in waters that are used for irrigation. The salt content of most irrigation waters ranges from 0.1 to 5 tons of salt to the acre-foot of water (approximately 70 to 3,500 parts per million). The amount of soluble salts in river waters in the Western States varies greatly—70 p. p. m. in the Columbia River at Wenatchee; 1,574 p. p. m. in the Sevier River near Delta, Utah; and 2,380 p. p. m. in the Pecos River at Carlsbad, N. Mex. The Colorado River, an important source of irrigation water in the Southwestern States, contains about 1 ton of soluble salts to an acre-foot of water (740 p. p. m.).

The salt content of a river may change downstream because of return flow from drainage and because of the solution of minerals as water moves along the river bed. The soluble salts in the Rio Grande, for example, increase from about 180 p. p. m. at Otowi Bridge, N. Mex., to 780 p. p. m. at El Paso, Texas, and 1,770 p. p. m. at Fort Quitman, Tex. The concentration of salt in the lower Rio Grande, however, drops because of the lower concentration of salts in some of the tributaries, so that at Rio Grande City, Tex., more than 900 miles down the river from Fort Quitman, the amount of soluble salts is only about 525 p. p. m.

The range in salt concentration in ground waters pumped from wells may be much greater than that of surface waters. Ground water from wells near each other may be different in salt concentration and composition.

Even the variations in water from different depths at a single location may be large. Analyses of many wells in the Coachella Valley, Calif., indicated a range in soluble salts from 130 p. p. m. to approximately 8,500 p. p. m. Two wells, 565 and 180 feet deep, within a half-mile of each other had salt concentrations of approximately 400 and 8,500 p. p. m., respectively.

The evaporation of moisture from the soil surface does not remove salt from the soil, and relatively little is absorbed by plant roots. Consequently the use of saline irrigation water results in the accumulation of soluble salts in the soil unless it is prevented by leaching and drainage. One can use irrigation water with a moderate degree of salinity, however, if drainage is adequate and enough irrigation water is applied so that some of it goes through the soil profile and out into the drainageways. In that event, the concentration of soluble salts in the water will restrict the crops that can be grown to those with moderate salt tolerance. If saline waters are used so sparingly that there is no excess for drainage, however, there will be an increase in the salinity of the soil.

Because of the potential salinity problem when saline irrigation waters are used, leaching and drainage must be provided to remove dissolved salts that would otherwise accumulate in the root zone or in the subsoil immediately below.

Carl S. Scofield referred to the relationship between the quantity of dis-

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solved salts delivered to an area with irrigation water, and the quantity removed from the area by the drainage water as the salt balance of the area. If a favorable salt balance is to be attained, the output of salts must be approximately equal to the input. When the salt balance is adverse, the input of salts exceeds the output. This condition must be avoided in a permanent irrigated agriculture.

THE SALINIZATION of soil affects the growth of crop plants in two ways.

The first is a reduction in the amount of water absorbed by the roots. That occurs because continued irrigation with saline water in the absence of a favorable salt balance results in a gradual but progressive increase in the osmotic pressure of the soil solution. Osmotic pressure is a measure of the soluble salts in solution and provides a method of expressing the concentration of the soil solution on an energy basis. Retardation of growth is virtually linear with increases in the osmotic pressure of the soil solution, and is largely independent of the kind of salts present. In extreme cases, a soil may become so saline that it will not even support the growth of halophytes (salt-tolerant plants), just as soils may become too dry to support the growth of xerophytes (plants adapted to growth under dry conditions).

The effect of a given amount of soluble salts in the soil solution is intensified as the soil moisture content declines between irrigations—as indicated by the increase in the osmotic pressure of the soil solution that accompanies drying out. Furthermore, as a soil gradually dries following an irrigation, the surface attraction of the soil for water, known as soil-moisture tension, increases. Soil-moisture stress is defined as the osmotic pressure of the soil solution plus the soil-moisture tension.

Experiments by C. H. Wadleigh and others in 1946 and 1948 have shown that, if other factors are not limiting, the vegetative growth of crop plants is closely related to the average soil-moisture stress. Also, it has been shown that the absorption of water from the soil by plant roots depends upon the soil-moisture stress. Thus, one of the main effects of soil salinity is to limit the water supply of the plant. This induces modifications in growth that are usually associated with a lack of water in the plant tissue.

Wide variations among irrigation waters may exist with respect to the kinds of salts present, as well as with the amount of salts in solution. Salts, when dissolved in water, dissociate or separate into chemically equivalent amounts of positively and negatively charged particles—ions. The positive ions are cations. The negative ions are anions.

The major ions in irrigation water are the cations calcium, magnesium, and sodium; and the anions bicarbonate, sulfate, and chloride. Other ions that may be present are potassium, carbonate, nitrate, silica, iron, and boron, but they are usually found in low concentrations. Occasionally waters may be high in bicarbonates and, less frequently, in nitrates. In waters of low total salt concentration, bicarbonates frequently exceed the combined sulfate and chloride content, but in rivers with higher salt content, such as the Arkansas, Colorado, Gila, Pecos, and Rio Grande, the predominant salts are sulfates or chlorides.

Sodium salts are usually present in irrigation waters, and if the proportion of sodium is high, it may be adsorbed on the soil particles and result in an unfavorable physical condition. Such soils, when they are wet, tend to run together and impede the movement of water and air. They form hard clods when dry. Irrigation waters with high sodium percentages therefore may require special management practices.

The use of waters that are low in total salts but high in bicarbonate aggravates the sodium problem. Water that is relatively low in total salts and has a sodium percentage ($Na \times 100$/total cations) that is within safe limits may be questionable if the amount of

bicarbonate is considerably in excess of the calcium and magnesium present. This excess bicarbonate over calcium plus magnesium is referred to as residual sodium carbonate. The occurrence of residual sodium carbonate is fairly common in the Western States. Out of a group of approximately 450 well and stream supplies in the San Joaquin Valley, slightly more than half contained residual sodium carbonate. This condition also occurs in many other places—in the White River, South Dakota; the Sevier River, Utah; the Humboldt River, Nevada; and the Nile River in Egypt.

When an irrigation water containing residual sodium carbonate evaporates in the soil, calcium and magnesium carbonates precipitate, and the sodium percentage of the soil solution increases. Then sodium replaces calcium on the soil particles, the exchangeable-sodium percentage of the soil increases, and the physical condition of the soil, especially the permeability, may be impaired. In addition, the pH may increase and organic matter may be dissolved, giving the dark color typical of a so-called black alkali soil.

Some salts or ions that are harmless in low concentrations may accumulate in the soil solution in sufficient amounts to cause toxic reactions in plants. The ions most likely to cause such reactions are sodium, chloride, bicarbonate, and sulfate. Less frequently, crops grown in soils having excessive amounts of calcium and magnesium may show toxic symptoms. Selenium, lithium, and fluoride are found in a few waters and soils, and may be accumulated in plant tissues. Ordinarily selenium and fluoride do not affect plant growth but may have serious effects on animal life. A fraction of a part per million of lithium in irrigation water produces tip and marginal burning and defoliation of citrus leaves.

Besides the indirect effects of sodium on plant growth resulting from adverse modifications of the physical properties of the soil, there is some evidence of its specific toxicity. If the sodium content of the soil is high, almonds may develop tipburn and avocados a leaf scorch. Leaf burn in salt-sensitive cotton varieties has been correlated with high sodium content in the leaves. Other common cations affect specific crops. An example is guayule, a rubber-producing shrub native to North America, which grows poorly in the presence of only moderate amounts of soluble magnesium.

The accumulation of the chloride ion in plant tissues frequently results in toxic symptoms. Among the crop plants that are sensitive to the chloride ion are peaches and other stone fruits, pecans, some citrus varieties, avocados, and some grapes. Many species are no more sensitive to chloride than to equal concentrations of sulfate salts. Specific sensitivity to high concentrations of the sulfate ion have been reported for tomato, flax, cotton, and orchardgrass.

The bicarbonate ion is toxic because its accumulation in the soil solution affects mineral nutrition and tends to reduce the availability of iron in many plants. Apple orchards in Washington become chlorotic when irrigated with water high in bicarbonates. Continued use of such a water may seriously affect the mineral nutrition of the tree. Specific toxicity of the bicarbonate ion has also been demonstrated with Dallis grass. A reduction in the growth of beans accompanied by chlorosis becomes more pronounced with increasing concentrations of bicarbonate. On the other hand, garden beets are much more tolerant to bicarbonate.

Boron is a minor constituent of practically all natural waters. Irrigation waters should be analyzed for it if one suspects its presence at toxic levels. Boron is essential to the growth of plants, but it may be toxic at concentrations only slightly in excess of those needed for optimum growth.

Toxicity may develop with boron-sensitive crops when the concentration is as low as one part per million (1 p. p. m.). Water containing 1 p. p. m. or less of boron may be regarded as

excellent. For most crops, however, water that contains 1 to 2 p. p. m. is satisfactory. Water up to 3 p. p. m. may be used with the more boron-tolerant crops. Water containing more than 3 p. p. m. is doubtful or definitely unsuitable for irrigation purposes. Boron is responsible for symptoms of toxicity that have appeared on citrus and walnut trees in southern California and on those and other crops elsewhere.

Irrigation waters are classified on the basis of the more important constituents in solution so that the effect of the water on crops and on soils can be anticipated with some assurance. Such classifications assume that the water will be used under average conditions with respect to climate, amount of water used, drainage, texture and permeability, and salt tolerance of the crop. Under unusual circumstances it may be possible to use a water that under average conditions would be considered unsafe. Conversely, under some conditions, it may not be safe to use a "good" water.

The United States Salinity Laboratory has proposed a scheme for classifying irrigation waters on the basis of two main factors. Waters are divided into four classes with respect to salt concentration, the salinity hazard, and into four other classes with respect to the probable extent to which soil will absorb sodium from the water and the length of time required to adversely affect the soil (the sodium hazard). The characteristics of irrigation water based on these two criteria are determined by chemical measurements and are assigned values that indicate the overall water quality.

A PROBLEM of great economic importance to the farmer arises when salinity or alkali conditions develop in good farmlands. This can occur as a result of natural causes, such as salty ground water and poor drainage, or from manmade causes, such as the application of irrigation water of poor quality, improper soil management, and lack of drainage facilities, or from some combination of these factors.

Saline and alkali soils contain excessive concentrations of either soluble salts or adsorbed sodium (alkali) or both. The original sources of these salt constituents are the primary minerals found in soils and in the exposed rocks of the earth's crust. As a result of chemical decomposition and physical weathering, the soluble constituents are gradually released from the minerals. These soluble salts in humid areas are carried downward by rain into the ground water and ultimately are transported by streams to the oceans. Leaching usually is local in nature in arid regions, and the soluble salts may not be transported far. This is so because there is less rainfall to leach the soluble salts out of the soil and transport them away and because the high evaporation rates characteristic of arid climates tend to concentrate the salts in ground waters and in soils.

Inadequate drainage is associated with and contributes to the severity of saline and alkali soil conditions. Because of the low rainfall in arid regions, surface drainageways may be poorly developed, and consequently drainage basins may have no outlet to permanent streams. The salt-bearing waters drain from the surrounding high lands of the basin to the lower lands, and may temporarily flood the soil surface or form permanent salty lakes.

Saline and alkali soil problems most often develop as a result of the irrigation of level valley lands, which may be nonsaline and well drained under natural conditions but may have drainage facilities inadequate to take care of the additional ground water resulting from irrigation practices. In that event, the ground-water level may be raised from a considerable depth to within a few feet of the soil surface in a relatively short time. When that occurs, the water moves upward to the soil surface as a result of evaporation and plant use. This increases the salt content of the surface soils and of the

soil water in the root zone, forming problem soils varying from a few acres to hundreds of square miles in area.

Soil deterioration frequently results from the application of either good or poor irrigation water to soils with impaired drainage, since in this case the accumulation of soluble salts cannot be prevented. Saline and alkali problems also arise if drainage facilities are adequate but insufficient irrigation water is applied to provide for the necessary leaching of excess salts.

A SALINE SOIL contains enough soluble salts so distributed in the soil that they interfere with the growth of most crop plants. Ordinarily the soil is only slightly alkaline in reaction (pH 7.0 to 8.5) and contains very little adsorbed sodium. Saline soils are often recognized by the presence of white salt crusts; by damp, oily-looking surfaces devoid of vegetation; by stunted growth of crop plants, with considerable variability in size and with a deep blue-green foliage; and sometimes by tipburn and firing of the margins of leaves. Chemical and electrical-conductivity measurements rather than observations, however, are commonly used for assessing soil salinity. The determination of salinity status in terms of plant response should take into account the moisture-holding capacity of the soil in addition to its salt content.

The water required for the growth processes of plants is absorbed by the roots from the soil solution. Many crop plants absorb and transpire or evaporate 500 pounds of water in a season for each pound of dry matter produced. The soil moisture in arid regions is replenished by irrigation with water containing appreciable amounts of soluble salts, or by upward movement of more or less saline ground waters. In either instance, soluble salts are added to the soil with each application of water. Also, the concentration is increased between each irrigation through loss of water by evaporation from the soil, as well as by plant transpiration. And, as we mentioned earlier, the total concentration of the soluble salts, rather than their chemical nature, is mainly responsible for the harmful effects of saline soils on crop growth.

Often it is not economically feasible to maintain a condition of low salinity in a soil. The reason may be the extreme salinity of the irrigation water, the cost of providing adequate drainage, or the inherently low permeability of the soil. Then the farmer has to learn to live with the salt.

He can adopt management practices that minimize the effects of salinity, and he can make a judicious selection of crops or crop varieties that will produce satisfactory yields under moderately saline conditions. In selecting crops for saline soils, particular attention should be given to the salt tolerance of the crop during germination.

Poor crops frequently result from a failure to obtain a satisfactory stand. It is possible to modify planting practices to minimize the accumulation of salt around the seed and to improve the stand of crops under saline conditions. Recommended management practices and the salt tolerance of many species and varieties of crop plants are listed in the Department of Agriculture Handbook 60, *Diagnosis and Improvement of Saline and Alkali Soils*.

The chemical characteristics of saline soils are determined chiefly by the kinds and amounts of salts present.

Soil particles, as a consequence of electrical charges on their surfaces, adsorb and retain cations such as sodium, calcium, and magnesium. The adsorbed ions are combined with the soil particle, but they can interchange freely with other ions in the soil solution. This reaction is called cation exchange. The proportion of the various cations on the exchange complex is related to their concentration in the soil solution. Calcium and magnesium are less easily exchangeable than sodium. Since sodium salts seldom make up more than half of the soluble constituents of saline soils, very little sodium is adsorbed by the clay particles. Therefore the adsorbed ions in

saline soils are principally calcium and magnesium. Such clays are stable in water, are easily worked into granules and crumbs, and help produce a desirable environment for seed germination and plant growth.

Because of the presence of excess salts and the absence of significant amounts of adsorbed sodium, saline soils generally are flocculated; and, as a consequence, their permeability is equal to or higher than that of similar nonsaline soils. Consequently, if adequate drainage is provided, the excess soluble salts may be removed by leaching with ordinary irrigation.

An alkali (or sodium) soil contains sufficient adsorbed (exchangeable) sodium to interfere with the growth of most crop plants. The soil may be highly alkaline in reaction but does not contain excessive amounts of soluble salts. These soils correspond to "black alkali" soils and frequently occur in small irregular areas called "slick spots." Sodium usually becomes the dominant cation in alkali soils either through the accumulation of sodium salts or as a result of the precipitation of calcium and magnesium salts.

As the proportion of exchangeable sodium increases, soils tend to become dispersed and impermeable to water and air. Because the partially sodium saturated clay is highly dispersed, it may be transported downward through the soil and accumulate at lower levels, where the soil may develop into a dense layer with a columnar structure, having a low permeability. It becomes increasingly difficult to replenish the water supply of the root zone by irrigation, and also more difficult to establish a condition of surface tilth favorable for seed germination and seedling growth.

Alkali soils may be improved or reclaimed by the replacement of the harmful exchangeable sodium by beneficial calcium and magnesium. That is generally accomplished by the addition of chemical amendments, the kind and the amount depending upon the soil characteristics, the desired rate of replacement, and economic considerations. Chemical tests are used to obtain estimates of the amounts of chemical amendments needed to reduce the exchangeable sodium to a given level. Sodium is relatively easy to replace, so the amount of calcium that must be added to insure replacement is only slightly in excess of the sodium present. The sodium released must be removed by leaching with water to insure completion of the reaction.

The choice of an amendment may be influenced by the time required for its reaction in the soil. In general, the cheaper amendments are slower to react. Consequently, if immediate replacement of exchangeable sodium is desired, one of the quicker acting, but more expensive, amendments will be needed. Because of its high solubility in water, calcium chloride is probably the most readily available source of soluble calcium, but it is seldom used because of its cost. Sulfuric acid and iron and aluminum sulfates that hydrolyze readily in the soil to form sulfuric acid are also quick-acting and relatively expensive amendments. Lime-sulfur, sulfur, sulfur-containing gases, and other acids are useful but generally are too expensive. These acids and acid-forming amendments should be used only on calcareous soils because they react with limestone (calcium carbonate) to release soluble calcium, which replaces the adsorbed sodium. Because of its comparatively low cost, gypsum is the most common amendment used for reclamation. The rate of reaction of gypsum is limited only by its relatively low solubility in water.

Except in places where sulfur is used, alkali soils should be leached immediately following the application of the amendments. Leaching dissolves and carries the amendment downward and removes the soluble sodium replaced by calcium-bearing amendments.

The reclamation of alkali soils involves more than replacement of the

adsorbed sodium, however. A good physical condition must be restored. That involves the rearrangement and aggregation of soil particles to form soil granules which produce good tilth. Good soil structure is promoted by alternate wetting and drying, and freezing and thawing, and by the action of plant roots and organic matter.

A SALINE-ALKALI SOIL contains excessive quantities of both soluble salts and adsorbed sodium so distributed that the growth of most crop plants is reduced. The soil is seldom highly alkaline (pH above 8.5) in reaction. The soils form as a result of the combined processes of salinization and the adsorption of sodium. As long as excess salts are present, the appearance and properties of these soils usually are similar to those of saline soils. If the excess soluble salts are leached out, the soil properties may change markedly and become similar to those of alkali soils. They become strongly alkaline, the particles disperse, and the soil becomes unfavorable for the entry and movement of water and gases and for tillage.

The management of saline-alkali soils is then similar to that of alkali soils. That is, the soluble salts and exchangeable sodium must be removed by the addition of amendments followed by leaching. In theory, it is economical to leach out most of the soluble salts before the application of amendments. That is not recommended, however, because the permeability of saline-alkali soils declines markedly upon leaching and the rate of reclamation is retarded. Saline-alkali soils often contain gypsum. When such soils are leached, the gypsum dissolves and the replacement of exchangeable sodium by calcium takes place concurrently with the removal of the excess salts.

THE HISTORY of irrigation development in this country and elsewhere shows that, while some failures may be assigned to unfavorable economic or social conditions, and a few to lack of adequate engineering, most failures have been due to unfavorable conditions of water, soil, and drainage.

Many people have learned through experience that the productivity of some irrigated land may be relatively short-lived. On the other hand, many irrigated areas are very successful and continue to be highly productive for a long time. It seems clear that long-continued irrigation farming can be practicable where conditions are favorable. Furthermore, if the causes of failure are ascertained and clearly understood, methods of avoiding failure may be devised and used.

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Planning a Large Irrigation Project

John R. Riter and Charles LeMoyne, Jr.

A large-scale irrigation development is a substantial undertaking that requires investigation, planning, and progress in accordance with a defined course of action. It is interwoven with economic, social, legal, political, and interregional or international problems. It has to take into account three basic elements, land, water, and people, and requires the combined skills of many professions.

Planning embraces study of the whole drainage area or basin to obtain the maximum benefit from use of the known natural resources. The planning is not difficult in itself. It is an interesting and inviting work, which calls for vision, commonsense, and willingness to accept new ideas and reject ideas that limit development short of the ultimate. As planning moves into the stage of active physical development and proceeds through the various steps of construction, there is need for review and a restudy as changed conditions affect the irrigation plan or as required to provide for future development. Flexibility is important.

The reconnaissance stage, the first stage of planning, involves a shortcut review of all major engineering, land, and water problems to determine whether more detailed investigation is warranted. The aim is to narrow the field for detailed study of the items that pertain to the best final plan.

Reconnaissance planning deals only with major factors and with those only in general terms. Men assigned to the task are men with extensive experience. Only a few men need be called upon to make a reconnaissance to evaluate the irrigation potentialities of lands and water. The primary objective is to develop an irrigation project, yet the overriding concept of maximum possible development should not be overlooked and may have significant bearing on decisions.

Before a final plan is adopted, an on-the-ground study has to be made. Because many possible uses of water exist, the possibilities of water development should be evaluated in relation to irrigation, such as hydroelectric power; domestic, municipal, and industrial water supply; flood control; navigation; public health; fish and wildlife; recreation; and salinity control for maximum basin development. In irrigated areas, the limiting factor of water often dictates the extent to which water is developed for irrigation and for other purposes.

Planning during the feasibility stage, the second stage, should be detailed and conclusive in the formulation of plans for the irrigation project, recognizing that the plan proposed now may be subject to change when the irrigation project is being constructed.

Planning during this stage follows rather definite procedures.

Recognizing the importance of water, various Federal and State agencies have compiled information on the runoff of streams and collected climatological data. When adequate data are not available to determine the potential water supply, however, the missing information may have to be estimated. Information also is needed about the amount and the distribution of water each year, the use of water by those having prior rights on a stream, the amount of surplus water that can be regulated, the time when the surplus occurs, and the possibilities of storing surplus flows in years of high runoff.

Large-scale irrigation projects often combine the use of surface and subsurface supplies to provide the full requirements. Therefore study has to be made of ground-water possibilities. An analysis of all surface and subsurface water supply records with respect to critically short, normal, and flood flows leads to determination of the

sizes and complexity of the engineering works needed. These studies, together with analyses of the physical situation, may indicate the possibility of making a many-purpose project.

The quality of the water that will be available also must be determined. The soils suitable for irrigation and crops to be grown may be limited by the quality of the water. Existing rights to water may be adversely affected by irrigation if the quality is changed materially by the use of return flows from the irrigated lands.

Flood flows require a special consideration; major storage or diversion structures on the streams must be designed with adequate spillways or outlets to accommodate them. Proper design will insure stability of dams and control works and, in turn, stability of the irrigation project. Users of the water need assurance that once water is made available for irrigation, it will be available when it is required.

Interstate streams generally have their own laws. Rights to the use of water are subject to the constitutions, statutes, compacts, treaties, and court decisions of the countries and States through which it flows. The total of composite authority constitutes the law of the river. Plans for use of its water must conform to that law.

The feasibility of an irrigation project depends on continuing productive ability of the land when water is made available. In the planning of an irrigation project, a thorough examination is made of the lands, which are classified as to physical and economic aspects. The land classification is basically an economic classification to determine the productive capabilities, production requirements, and amount of land development needed for sustained irrigated agriculture.

The general procedure followed in land classification commences with consideration of the general area and ends with the designation of irrigable lands to be served. Lands may be termed arable if they will have enough payment capacity when operated as irrigated farms to meet all production expenses, including annual water charges, and to provide a reasonable return to labor and capital. Lands are termed irrigable if they are the arable lands within irrigated farms to be provided with water under the selected engineering plan.

The fundamental considerations that are followed in making this evaluation are:

A study of land resources in a fully developed area that has physical and climatic conditions similar to the area under investigation;

Analysis of the probable influence of specific physical factors on the economics of production and costs of land and development in the area;

Separation of the physical factors into categories having approximately equal economic significance and the development of project land classification specifications;

Application of the land classification specifications to the arable classification;

Modification of the arable classification as additional physical, engineering, hydrologic, and economic information is obtained;

Completion of the irrigable classification or location of the specific lands found to be suitable for irrigation development under the project plan.

Land classification is performed in the field by appraisal of the soil characteristics and topographic and drainage features. A large amount of additional basic data relative to agronomy, economics, and engineering must be obtained and correlated with the physical and chemical characteristics of lands in the designation of land classes. Six classes of land are recognized—four irrigable, one temporarily nonirrigable, and one nonirrigable. The classes represent degrees of suitability for irrigation farming and are necessary primarily for the analyses of land use and repayment. The land classification data are recorded on topographic base maps or aerial photographs, which show the location of the

irrigable lands and the boundaries between land classes. The results of the field work are summarized in detailed technical reports.

If the water supply is the limiting factor, the arable land classification data and the underlying surveys are used as the basis for selecting the locations of the irrigable areas to be included in the irrigation project. But if land is the limiting factor, arable land classification data are used primarily as a basis of designing an irrigation system to serve the area.

THE APPLICATION of engineering skills and judgment is essential to the design and construction of works to deliver irrigation water to the land in controlled and adequate amounts for crop use. In that, the important steps are engineering surveys and explorations, including geological interpretations; preparation of preliminary designs and cost estimates; and the determination of annual operation, maintenance, and replacement costs. Engineering studies connected with water, land, and the physical features of the project are generally carried on at the same time. Continuous coordination is required therefore to eliminate unnecessary and costly work in making project plans.

Physical limitations—such as quantity of water available, amount and location of irrigable areas, possible storage sites, and construction problems—are evaluated during the engineering study. Engineers make surveys to determine the locations for storage dams and reservoirs, diversion dams, main canals, pumping plants, distribution systems, and the drainage system.

In the early stages of an investigation, a reconnaissance is usually made of the project as a preliminary to more detailed studies. The reconnaissance is general and is done as quickly and cheaply as possible. Elevtaions often are determined by an altimeter, and distances are scaled from available maps or obtained by speedometer readings. Information thus obtained normally gives the planning engineer the basic engineering data from which he can develop a program for more detailed engineering surveys.

The detailed surveys and explorations locate the main engineering features and get data to be used in preparation of the feasibility designs and estimates. Topographic mapping of reservoir areas and dam sites, the project area, and, in many instances, the location of the main canals must be completed early in the study. By means of aerial surveying, which provides topography of the desired accuracy, one can map large areas quickly. This new technique in surveying has not eliminated the need for extensive field surveys to provide additional data, however. Basic engineering surveys depend on the establishment of good horizontal and vertical surveys.

Geologic studies provide basic data on earth materials and subsurface conditions necessary for the design of dams, tunnels, pumping plants, and canals. Similar information is needed for the development of an adequate distribution and drainage system. Local materials that are considered for use during construction are tested to determine their suitability. Data on soil stability and permeability and other aspects that might influence the type and design of the structures are obtained. All data are made available to the engineers responsible for the preparation of feasibility designs.

During the preparation of feasibility designs, studies are made to determine the structures best suited to the conditions encountered. Engineering economics is important: The engineer must design a structure for the job—the most economical in first cost and in annual cost of operation, maintenance, and replacement. He must also be mindful of other responsibilities in the construction of new works—protection of human life, protection to existing improvements, and the responsibility for sound and progressive development.

When feasibility designs have been completed and the quantities of materials necessary for construction have been estimated, the engineer can determine the cost of the structure by applying current prices for labor and materials to the estimated quantities of work and materials. The end product of the many individual designs and estimates is the estimated cost of construction. To that figure must be added an amount to cover the costs of the engineering, supervision, and administration needed to finish the project.

An annual cost that represents the sum of costs of annual operation, maintenance, and replacements necessary to keep the irrigation project in good operating condition must be determined. Estimating that cost often is more difficult than determining the construction cost.

To make a reasonable estimate of the annual operation, maintenance, and replacement costs, the project plan must be crystallized, extensive information on each important structure must be available, and the farm unit layout must be determined. With such data available, an organization necessary for the operation and maintenance can be planned, equipment requirements can be estimated, materials and supplies needed for operation and maintenance can be determined, and the probable life of features needing replacement can be calculated. By pricing such items, an annual cost representing the average expected expenditure that will be required each year to keep the project operating in good condition is obtained.

Repayment studies are made to determine payment capacity of the water users and to make recommendations for repayment of construction costs allocated to irrigation. Determination of payment capacity is accomplished by an extensive study of the agricultural expectancies of the project area without the proposed development in comparison with conditions assumed to exist under the proposed development. The main tool of this study is the farm budget analysis. The construction of farm budgets requires accuracy in selecting and testing data, particularly those relating to existing district debts, price base, yields, input requirements, managerial ability, level of land use, size of farms, family living allowance, and interest costs. The analysis is the basis for irrigation assessment. It is used also in preparing a summary financial analysis.

The recommended repayment is defined as the annual payment, reasonably expected from water users in the project area, which could be applied toward retirement of the allocated construction cost. The elements necessary for this estimate are the estimated payment capacity, the allocated irrigation construction charge, and the estimated operation, maintenance, and replacement costs.

Since most large-scale irrigation developments are portions of multipurpose projects, estimated irrigation construction costs are often determined by an analysis and allocation of total project development costs to the several project purposes.

The costs generally fall into nonreimbursable and reimbursable categories. The reimbursable costs may be further divided into non-interest-bearing costs and interest-bearing costs. It is relatively easy to determine specific costs, but the proper distribution of joint costs is often a problem.

The following methods for allocating joint costs of project works are considered the most acceptable: The separable costs-remaining benefits method; the alternative justifiable expenditure method; and the use-of-facilities method. These methods are not all equally applicable, nor would any one yield a satisfactory solution at all times. The selection and application of any method should be based on existing laws and policies, with the aim of providing an equitable basis for allocation and apportionment of construction costs to the several purposes served. With the construction costs and operation, maintenance, and replace-

ment costs allocated and revenues known, it becomes possible to prepare a repayment analysis.

In the preparation of a comprehensive repayment analysis, all costs that will be incurred in the development of a large-scale irrigation project must be anticipated as to amount and time of occurrence. All revenues that reasonably are expected to be available as a direct result of this development must be anticipated as to amount and time of occurrence. This information forms the basis for a repayment analysis of the potential development.

Results of the repayment analysis will disclose what the project can pay toward the costs of construction in any number of years. When the project has the ability to return within a reasonable time the costs incurred for its construction and to meet estimated annual costs of operation, maintenance, and replacement, the project can be shown to be financially feasible and worthy of construction.

Project development may be further justified by a comparison of the net benefits resulting from construction of the project with all anticipated costs of bringing about those benefits. A ratio of all net benefits to costs in excess of unity will indicate the desirability of the development.

Timely and adequate planning will eliminate proposals that are undesirable and not economically feasible.

Assume that a large-scale irrigation project planned in considerable detail has been found feasible, local interests recommend its construction, and necessary arrangements have been made for financing and to insure repayment. To proceed with the development, additional steps are now in order. They include obtaining additional detailed field data not required during the planning of the project but needed for preparation of the final designs; issuing designs and specifications; preparation of construction drawings; and obtaining necessary rights-of-way.

Sufficient time is allowed before beginning construction to insure completion of designs on features that will be constructed in the early stages. The features usually scheduled for early construction are the construction camp, access roads, water system, and power lines. During the planning of the project, a proposed construction schedule is established for the component features. The schedule is reviewed and, if necessary, adjusted so that it may be used as a firm basis for carrying out the construction program.

Complete coordination and cooperation are maintained between the design engineers and the construction engineers to insure the issuance of designs and specifications on schedule and to correct or alleviate delays during construction. Inspection trips to the project by responsible designers and visits to the design office by field engineers make this close liaison a reality, provide a clear understanding of design and construction problems, and promote maximum efficiency.

No matter how carefully a project is planned, changes may be necessary during construction. Changes could result from undiscovered subsurface conditions or different requirements resulting from changed conditions of various kinds. Even the best plans are subject to change, and the builders and designers have to be able to meet them.

A further problem of considerable significance must be recognized as occurring during development. As major features are completed, but not used or fully used, a need arises to provide personnel, materials, and equipment to insure the safety of the structures and, as necessary, to operate and maintain them to assure their continued usability. This requirement is recognized during the planning of the project but is made a responsibility of the construction or operating group and must not be overlooked. Large-scale irrigation projects often are developed by blocks or units of land that may extend construction over periods of 10 or 20 years.

As water becomes available for irrigation, a further problem enters the development picture—the establishment of farmers on new farm units.

SOMETIMES THE FARMERS are not familiar with the problems connected with irrigation farming, the need for the preparation of the lands to receive irrigation water, and the controlled application of water for best results. They may need help, which can be made available through county, State, and Federal agencies in various ways. When a large-scale irrigation project has been well planned, properly constructed, and the farmers have been given adequate instruction and assistance, the project will move forward and benefit the individual owner and the State and Nation as well.

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Water Is Where the Irrigator Finds It

William P. Law, Jr., and George M. Renfro, Jr.

Water for irrigation in the eastern part of the United States comes from three general sources: The perennial streams; ponds, reservoirs, and lakes; and ground water. Nearly always is each of the sources developed on the farm itself. Few organized irrigation enterprises exist in the East, because demands for irrigation water have not been heavy enough, and few Eastern States have laws for the creation of irrigation districts and similar enterprises.

Many farmers, however, would like to irrigate but have no source of water that can be developed on their own farms. Irrigation in the humid areas has expanded although rainfall averages 20 to 30 inches in the growing season—enough water to make it seem that the need for irrigation would be small. But the rainfall may be distributed unevenly; often it is excessive at some time during the growing season and too light in other periods. It is to get water for irrigation during those drought periods that some farmers need to develop additional sources.

THE USE of yearlong streams, usually rivers or the larger creeks, because of the doctrine of riparian rights that exists in most States in the humid areas, is limited to farms—a small percentage of the farms—on the streams. The streams depend on rainfall, and as a rule their rates of flow fluctuate widely throughout the year. The flow of the smaller streams is usually lowest during long dry periods, when water needs are greatest.

A perennial stream is a dependable source only as long as the acreage to be irrigated will need no more water than the stream will produce during the longest droughts. When the acreage to be irrigated requires more water than the dry-weather flow, the waters of the stream must be impounded to insure an adequate source. The intermittent streams are not dependable unless their water can be impounded.

The rate of dependable flow required when irrigating directly from a stream depends on the size of the irrigated area, the moisture requirements of the crops during periods of peak use, the efficiency of the distribution system on the farm, and the time it takes to finish one irrigation.

Irrigation in the humid areas is mostly by sprinklers. Most farmers prefer to irrigate in the daytime; thus they make no use of the streamflow during the night, and a higher flow is required for irrigation of a given acreage than if irrigation were continuous.

For example: If a farmer wants to

apply 2.4 inches of water on an area in 6 days, irrigating 12 hours a day, he would need at least 15 gallons a minute for each irrigated acre. If the same depth of water were to be applied in the same number of days, irrigating 24 hours a day, the minimum rate of flow required would be only 7.5 gallons a minute. And if the farmer wants to complete one irrigation in 3 days instead of 6, the minimum rate of flow would have to be 30 gallons a minute.

Sometimes a farmer can store overnight flow within the banks of a stream by using a low dam equipped with flashboards or some other means of control. Sometimes he can divert overnight flow through a pipe or open ditch into a small reservoir or pit excavated near the stream. Thus he could make use of the entire streamflow.

A FARMER needs to know the dry-weather flow in a stream before planning for irrigation.

First he should find out whether the stream has been gaged by the Geological Survey or some other Federal or State agency. If it has not been, he will have to arrange to measure the streamflow during a long dry period. There are several ways to do that, the choice depending on the size of the stream.

The method of irrigation usually governs the method of conveying the water from the stream to the fields. In the sprinkler method, the water is conveyed under pressure in pipelines to the fields. Pressure is supplied by a pump on the streambank. In places where surface or subsurface methods are used, the water is usually pumped into open ditches and conveyed to the irrigated fields by gravity.

The quality of water in streams in the humid areas is generally satisfactory for irrigation purposes. Sometimes, however, streams in industrial localities may be polluted with industrial wastes to a degree that is injurious to plant growth. If any doubt exists as to the suitability of water for irrigation, samples should be collected at intervals and analyzed in a laboratory. Local representatives of agricultural agencies can tell the farmer about the laboratory services.

The mouths of streams along the Atlantic and Gulf Coasts are influenced by tidal fluctuations and often contain excessive amounts of harmful salts as to be unfit for irrigation. Automatic tide gates may be installed in the smaller streams. The gates are opened to permit the flow of fresh water at low tide and closed to keep out sea water at high tide. Some farmers use tidal streams by irrigating only at periods of low tide, when fresh water is running in them. In any event, the tidal streams should be used for irrigation only after chemical analyses have shown that their waters are suitable.

The rights of a farmer to use water from streams in the humid areas are governed by the riparian doctrine. Under the rules of common law, an owner of land along a stream was entitled to have the streamflow to his land undiminished in quantity and unimpaired in quality except for use by upstream riparian owners for domestic purposes.

Under the modified doctrine of riparian rights that now prevails in some of the Eastern States, it is held that the riparian right includes the right to make use of the water for irrigation, among other purposes, and that such use is a property right that is entitled to protection like other property rights.

STORAGE PONDS or reservoirs are an increasingly important source of irrigation water. They usually are of the impounding type and made by constructing an earth dam across an intermittent or spring-fed stream. Water is impounded from drainage areas of 50 to 2,000 acres, dams are 10 to 30 feet high, and the reservoirs hold 10 to 300 acre-feet. The reservoirs are as near the irrigated fields as possible.

The acreage of crops irrigated from a farm pond must be limited to the acreage for which water will be available throughout the growing season. The capacity must be adequate to meet

the requirements of the crop and overcome the unavoidable water losses. Allowances are made for inflow expected during the growing period.

The required storage capacity of a farm pond used for irrigation is determined after considering the maximum seasonal requirements of the crops to be irrigated; the effective rainfall expected in the growing season; the application efficiency of the method of irrigation; the unavoidable losses due to seepage and evaporation; and the volume of dry-weather flow.

The seasonal water requirements of crops may be obtained from results of studies at experiment stations or estimated from weather data. The effective rainfall that can be expected during the growing season can be estimated only from a study of rainfall records over a long period. Rainfall in the growing season in the humid areas varies widely, and consideration can be given safely only to the amount of rainfall during the driest previous season. Rainfall of less than one-fourth inch in any one day should be disregarded, because such light precipitation usually is evaporated from the plant foliage and the ground surface and is not available to the roots. Allowances must also be made for rainfall lost because of runoff and deep percolation. The safe seasonal water requirement for any crop is estimated by subtracting the expected effective growing season rainfall from the seasonal water requirements or consumptive use of that crop.

Not all the water stored in a farm pond can be made available to the plant roots. No irrigation method is 100 percent efficient. The sprinkler method, for example, may lose about 30 percent of the water because of evaporation from the spray, evaporation from the foliage, unequal distribution of the water, and deep percolation. Losses due to deep percolation, however, can be reduced by operating the system efficiently.

The depth of water that might be lost because of evaporation can be estimated from a study of local evaporation records of the Weather Bureau.

The depth of water lost because of seepage depends on the permeability of the embankment materials, the foundation conditions, and the construction methods. A properly constructed embankment on a good foundation ordinarily should result in seepage losses of less than 3 inches a month.

The total storage capacity of a farm pond or reservoir thus can be estimated by adding all of the expected losses we mentioned to the seasonal requirements of irrigation water.

One of the design problems encountered in planning irrigation ponds and reservoirs is the hydrology of the drainage area or catchment basin. To assure that the water will be replenished often enough—at least once a year, and preferably twice—the drainage area must be large in relation to the capacity of the pond. Consequently a relatively high rate of runoff can be expected to result from high-intensity storms of infrequent occurrence. Except on small watersheds, this rate of runoff often is greater than can safely be accommodated in a grassed-earth spillway. A structural spillway is then used. Drop-inlet spillways are most common, but drop spillways and chutes occasionally are used.

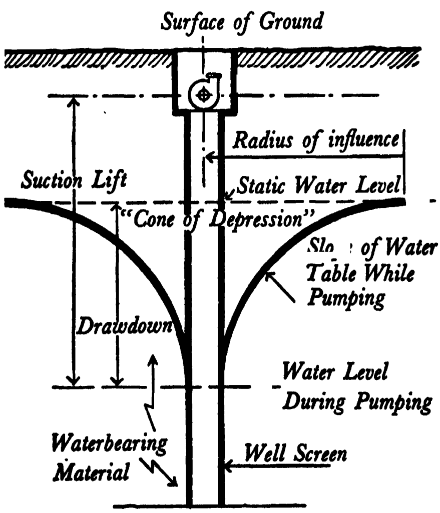
It is accepted practice to provide a structural spillway with a capacity which, when combined with the effects of temporary storage in the reservoir, will accommodate the expected runoff from the maximum storm that can be expected once in 25 years. As a precaution against overtopping, an emergency grassed-earth spillway is provided to accommodate greater storms than the 25-year design storm. Since every acre-foot of the reservoir capacity utilized for temporary storage reduces the capacity for storage of irrigation water, the temporary storage in reservoirs used for irrigation purposes usually is relatively small in relation to the total volume of runoff resulting from the design storm. It is necessary therefore to provide structural spillways of high capacities, often at con-

siderable expense. Sometimes the spillway costs as much as the embankment.

To reduce sedimentation, which can lower the storage capacity of a pond in a short time, it is advisable to select pond sites within watersheds protected by vegetation and containing a minimum of cultivated areas. If that is not possible, good conservation practices should be established within the watershed before the pond or reservoir is constructed.

The most common causes of failure of earth dams used to impound irrigation water are overtopping, because of insufficient spillway capacity; leakage through the dam or the foundation; and weaknesses in the arrangement of outlet conduits. All can be overcome by making adequate investigations and substantial designs and by adhering to specifications and prescribed construction methods.

The costs of storing water in the farm ponds or reservoirs are governed mostly by the topography of the site, but they often are influenced by foundation conditions, the kind of the embankment material, and the need for toe drainage. A compilation of the costs



Hydraulics of Wells

of a number of reservoirs in the Southeast indicated that the cost of impounding 1 acre-foot of water may be about 70 to 120 dollars.

NATURAL LAKES are not used widely as sources of irrigation water in the humid areas, except in Florida, where many lakes are used for the irrigation of citrus crops and occasionally for vegetables. Lakes usually furnish a desirable quality of water.

Their capacity often restricts the acreage that can be irrigated. Many of the same problems involved in using farm reservoirs pertain to lakes.

GROUND WATER is generally a more dependable source of irrigation water than are surface sources and is free from weed seeds and plant organisms. Wells usually can be located near the centers of irrigated areas for convenience and economy of pumping.

First costs of installing wells and well-pumping equipment usually are greater than the costs when using surface waters. Pumping lifts sometimes are higher. A danger exists of overdevelopment of the water-bearing strata by farmers, municipalities, and industries.

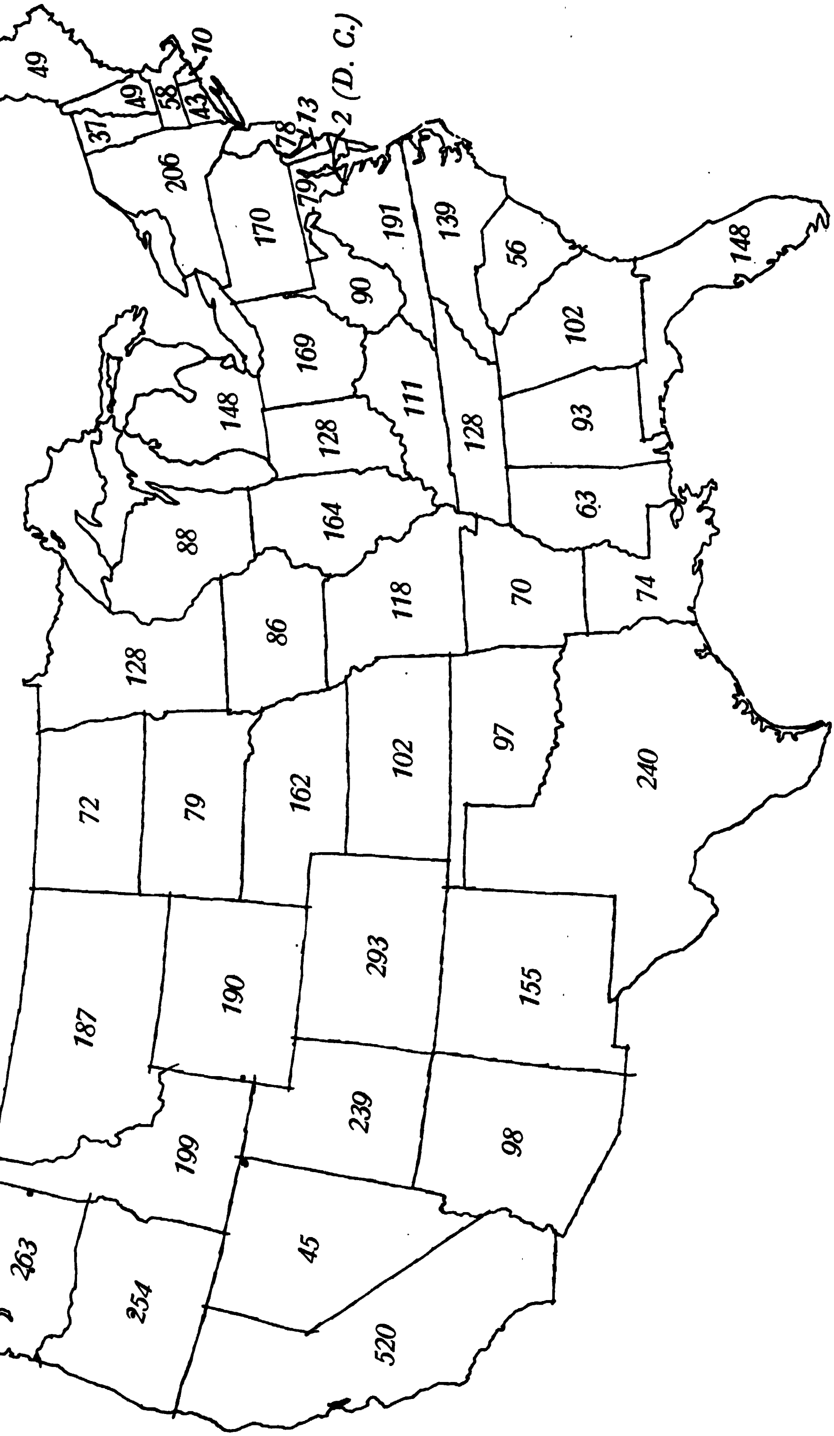
The best source of information about the availability of ground water is usually the State geologist. Local well drillers also can give helpful information.

The water-bearing strata—aquifers—vary greatly. By far the best aquifer is coarse gravel free of sand, but such formations are rare. Gravel formations generally are mixed with sands, silts, or clays. Gravel beds underlie much of the eastern part of the United States in the form of buried glacial drift and as buried beds of ancient meandering streams.

Cavernous limestone formations often yield large flows, but considerable chance is involved in getting good flows, because limestone frequently is solid and impermeable.

Fine sands and some sandstones generally yield satisfactory flows. Shales, clays, clay-cemented sandstones, and

Number of Active Discharge Stations, June 30, 1955



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rock of low permeability yield small flows. If fracturing is extensive, impermeable rock formations often yield appreciable flows, but they cannot often be maintained to meet irrigation requirements because of limited storage in the rock.

The type of well will depend generally on what equipment is available in the locality. That, in turn, is determined by local geologic conditions.

Hand-dug wells, once the common type, are nearly obsolete because of cost of labor and difficulty in obtaining the required depths. In some places, where the water table is near the surface, cylindrical wells are dug with power equipment, such as "clam shell" and "orange peel" buckets.

Pits, or excavated ponds, are a type of dug well in which greater storage capacity has been provided. They usually are rectangular and one-tenth to one-fourth acre in size and are excavated into water-bearing strata at depths of 10 to 20 feet. They are not always dependable because the water level may drop in the shallow strata in dry periods, but sometimes they provide water at a lower unit cost than do impounding-type ponds. The water in the pits sometimes may be increased by recharging them with clear drainage water or with water from small, deeper wells.

In radial wells, another variation of the dug well, collecting pipes are driven horizontally from the bottom of the excavated well. In shallow water-bearing strata they sometimes yield large flows, but they are expensive and may dewater the strata at an excessive rate.

Driven wells are commonly used in obtaining small flows of water from formations that permit driving. They consist of a drive pipe that has a point and screen at its lower end. The well is usually considered finished when it is driven into place, but development by pumping or surging will generally result in larger flows.

Driven wells do not often yield as much as 50 gallons a minute, but substantial flows are often obtained by connecting several driven wells, called a battery of wells, to a common pump suction tube, or manifold. To avoid excessive interference between wells, they should be properly spaced and in a line perpendicular to the direction of underground flow, if the direction can be determined.

Horizontal wells, a variation of the radial well, consist of collection screens and pipe installed horizontally, or nearly so, and are sometimes driven under streams or trenched across shallow underground streamflows and then covered.

Bored wells, dug with auger-buckets, are practically obsolete because of their limited application. It is hard to use augers in formations that require casing, and other methods of continuing the drilling must be used after loose water-bearing material has been reached.

Drilled wells are the most common type of modern irrigation wells. The drilling may be done by percussion tools, also known as cable tools; by rotating bits, called rotary tools; or by jetting, which employs both a jet and a simple bit. In cable-tool drilling, the material is loosened by the impact of the bit, mixed with water in the hole, and then removed by bailing with a long, slender, valve-bottomed bucket. In rotary drilling and jetting, the loosened material is forced to the surface by water, which is pumped down through the drilling pipe with enough pressure to raise the material.

A well must usually be developed, after it is drilled, to achieve maximum flow, especially when it is in formations containing sand, silt, or clay. Development consists of the removal of sand, silt, and clay particles and rearrangement of remaining material around the well screen by surging, backwashing, or hard pumping with quick stops and starts.

If sufficient gravel is not already present in the aquifer, gravel may be placed around the well screen artificially to aid in development of the well.

Development by blasting is sometimes resorted to in rock or limestone formations, but it involves the risk of ruining the well and losing cable tools. Muriatic acid has been pumped into wells in limestone formations to enlarge crevices and increase the flow.

Sustained pumping tests, to determine the yield of a well after several days of pumping, are necessary to establish its true capacity and dependability. Expensive pumping units should not be installed until yield under sustained pumping has been determined.

If economically attainable flows are too small for irrigating directly from a well, then surface reservoirs, such as pits, ponds, and ditches, may be used to advantage. By pumping from the well into a reservoir for some time, water will be available in quantity when it is needed for irrigation. Continuous operation of the well pump will replenish the surface reservoir between irrigations.

During a period of pumping, the water table is lowered temporarily around the well. This is the drawdown, and is necessary in every well in order to establish a slope, or pressure curve, that will cause water to flow to the well from the surrounding strata. The rate at which water can be pumped from a well is roughly proportional, within limits, to the drawdown. That is why wells should be deep enough. The radius of influence of wells increases with drawdown and with permeability of the aquifer. For wells in fine sands, the radius of influence may be less than 100 feet; for wells in coarse gravel aquifers it may extend to 2,000 or 3,000 feet.

When two wells are built closer together than twice their radius of influence, the flow of each well will be reduced somewhat, depending on the amount of overlap in their radii of influence. This helps to explain why doubling the size of a well (equivalent to putting two wells in the same hole) does not double the yield. Actually, a small increase in yield, generally 5 to 20 percent, is obtained by doubling the diameter of a well, because screening conditions are improved. Larger increases in flow may be obtained by adequate well spacing. For example: Two wells spaced one-fourth the radius of influence apart will yield about 75 percent more than either well singly; with a spacing of twice the radius of influence, the increase will be 100 percent.

Pumping from wells is generally done with turbine pumps. Centrifugal pumps cost less than turbines of the same capacity and may be used if the water table is near the surface and the drawdown is not excessive. The practical maximum suction lift of any pump is 22 feet at sea level or 17 feet at 5,000-feet elevation, but it should be kept below those limits for better pump efficiency and performance. Suction limit is the reason centrifugal pumps are sometimes installed in pits at the top of the well.

Suction lift is not a problem with turbine pumps because the working part of the pump is installed as near the bottom of the well as necessary. The pump may be driven by an engine-powered or electric-powered vertical drive shaft, or by a submersible electric motor close-coupled to the pump. The well diameter must be large enough to allow installation of a pump of the proper size.

Serious ground-water problems exist in the eastern half of the United States. The table has fallen near many industrial centers. The lowering of the water table, or the cone of depression, extends 30 miles or more around some cities, and has made necessary the repeated lowering of wells.

The reason is that the underground reservoir is not a continuous, unlimited, freely moving body of water. Water is lost continuously from underground strata through natural outflow and seepage. It is replenished naturally only by water that percolates downward from surface streams, forests, and fields. In years past, a condition of approximate equilibrium existed—the replenishment of the water table was

equal to its losses. But the replenishment rate has been reduced by land clearing, drainage, grazing, and cultivation; the withdrawal rate has been increased in many places by heavy pumping from wells. Whenever water is pumped from an area faster than it can be replenished from surrounding areas, the water level is bound to fall.

Two solutions to the problem of falling water tables are possible: Severely reducing the rate of pumping from wells or substantially increasing the rate at which the ground water is replenished by artificial recharge with excess surface water. The first is not a popular or desirable solution, although it is unavoidable if the second is neglected.

Artificial recharge is practiced but not on a scale large enough to satisfy our growing requirements. A few of the methods used are water spreading; directing water into abandoned wells, mine shafts, and open pits; and flowing water from city mains under pressure into active wells.

Two other possible sources of irrigation water are city water systems and sea water. Water from city mains, while usually too expensive and inaccessible for general farm use, has been used on some small acreages of high-value crops near a town. At 10 cents a 1,000 gallons, the water cost would be about 2.80 dollars an acre-inch, but pumping costs would be avoided. The use of desalted sea water for irrigation lies in the future.

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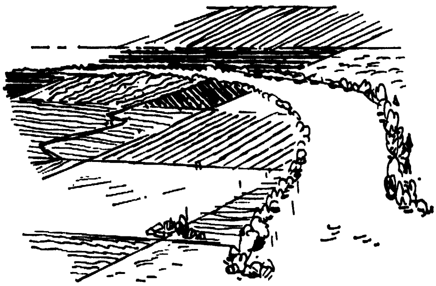
Water and Our Crops



Climate as an Index of Irrigation Needs

Harry F. Blaney

A large part of the irrigation water applied to farms is consumed by evaporation and transpiration. In field measurements it is hard to separate evaporation from transpiration, and the two processes are usually considered as one and called evapotranspiration or consumptive use.

Consumptive use includes all transpiration and evaporation losses from lands on which there is growth of vegetation of any kind, plus evaporation from bare land and from water surfaces. It is the best index of irrigation requirements. The irrigation requirement is the amount of water, exclusive of precipitation, that is needed for the production of crops. It includes plant transpiration, evaporation, deep percolation, and other economically unavoidable wastes.

Actual measurements of consumptive use under each of the physical and climatic conditions of any large area are expensive and time consuming. The results of research and measurements of the consumptive use of water, along with meteorological observations, provide basic data required for estimating water requirements for irrigated lands where few or no data, except climatological, may be available.

Many factors operate singly or in combination to influence the amounts of water consumed by plants. Their effects are not necessarily constant but may differ with locality and fluctuate from year to year. Some involve the human factor. Others are related to the natural influences—climate, water supply, soils, and topography.

Rainfall that comes in sufficient amounts during the growing season may lower the irrigation requirements. Light, summer showers of less than 0.5 inch may add little or nothing to soil moisture for plant transpiration and will be lost by evaporation. A large part of intense rainstorms may be lost by surface runoff. Winter and spring precipitation may store moisture in the soil to such an extent as to supply crop requirements during the early part of the growing season.

Temperature largely determines the types of crops most suitable for profitable production. The rate of use of water by crops in any particular locality is probably affected more by temperature than by any other factor. Abnormally low temperatures may retard plant growth and unusually high temperatures may produce dormancy. Consumptive use may vary widely even in years of equal accumulated temperatures because of deviations from the normal seasonal distribution, since transpiration is influenced not only by temperature but also by the area of leaf surface and the physiologic needs

of the plant, both of which are related to state of maturity.

Evaporation and transpiration are accelerated by days of low humidity and slowed during periods of high humidity. If the average relative humidity percentage is low during the growing season, a greater use of water by vegetation may be expected.

Evaporation of water from land and plant surfaces takes place much more rapidly when there is moving air than under calm air conditions. Hot, dry winds and other unusual wind conditions during the growing period affect the amount of water used.

The growing season, which is tied rather closely to temperature, has a major effect on the seasonal irrigation water needs of plants. It is frequently considered to be the period between killing frost, but it is shorter than the frost-free period for many annual crops, because they usually are planted after frosts are past and mature before frosts recur.

Although the growing season may be used as a guide for computing consumptive use and irrigation requirements, actual data on dates of planting and harvesting of crops and average annual dates of the first and last irrigation are important in determining the consumptive irrigation requirements of the crops. The normal length of the growing season ranges from fewer than 90 days in the high mountain valleys of Colorado to more than 360 days on the southern coast of California.

Latitude may hardly be called a climatic factor, but it does have considerable influence on the rate of the consumptive use of water by various plants. Because of the earth's movement and axial inclination, the hours of daylight during the summer are much greater in the northern latitudes than at the equator. The longer day may allow plant transpiration to continue for a longer period each day and to produce an effect similar to that of lengthening the growing season.

The available water supply for an area influences the type of crops grown and thus the irrigation requirement. In the arid and semiarid West where the major source is irrigation, both the quantity and seasonal distribution of the available supply will usually affect consumptive use. If water is plentiful, farmers tend to overirrigate in both frequency and depth of application. If the soil surface is frequently wet and the resulting evaporation is high, the consumptive use will likewise increase.

In some places the quality of the water also affects irrigation requirements, and as much as 20 percent more irrigation water is needed to control the accumulation of salts in the soil.

VARIOUS METHODS have been used to determine the amount of water consumed by agricultural crops and native vegetation. The source of water used by plantlife, whether from precipitation alone, or irrigation plus rainfall, or ground water plus precipitation, or irrigation plus ground water plus rainfall, bears on the selection of a method.

Unit values of consumptive use may be determined for different kinds of native vegetation and agricultural crops by soil moisture studies, lysimeter or tank measurements, analysis of irrigation data, analysis of climatological data, and other methods. For irrigated crops, data on the depth of the irrigation water, number of irrigations in a year, irrigation efficiency, water-holding capacity (field capacity) of soil, and length of growing season may be used in estimating unit values of consumptive use. Unit values observed in one area may be used in estimating consumptive use for other areas with somewhat similar climatic conditions, if temperature and precipitation records are available for both areas.

ESTIMATING CONSUMPTIVE USE of water from climatological and other data has been practiced by irrigation engineers for many years. C. R. Hedke developed the effective heat method for the Rio Grande Valley in 1924. Robert L. Lowry and Arthur F. John-

son in 1940 analyzed data on consumptive use from irrigated valleys and humid watersheds of wide differences in climate, latitude, elevation, and type of crops. They found a straight-line relation between annual consumptive use and heat supply expressed in terms of accumulated daily maximum temperatures above 32° F. during the growing season.

Scientists have developed methods for predicting evapotranspiration from climatic data. C. W. Thornthwaite, in 1948, outlined a procedure for determining potential evapotranspiration from atmospheric elements. At the Rothamsted Experiment Station in England, H. L. Penman and R. K. Schofield correlated evaporation from open water and evapotranspiration from grass with meteorological observations and developed an index for estimating evapotranspiration.

Studies by Karl V. Morin and me in 1941–42, in connection with the Pecos River Joint Investigations of the National Resources Planning Board, indicated that evaporation, evapotranspiration, mean monthly temperature, the percentage of daytime hours in a month, growing season, monthly precipitation, and efficiency of irrigation data could be used to estimate irrigation requirements. We developed formulas for computing rates of evaporation and consumptive use from temperature, daytime hours, and humidity records. In 1945, because mean humidity records were not readily available, Wayne D. Criddle and I simplified one of the Pecos formulas by eliminating the humidity factor.

THE PROCEDURE with the Blaney-Criddle formula is to correlate existing consumptive-use data for different crops with monthly temperature, percentage of daytime hours, precipitation, frost-free (growing) period, or irrigation season. The coefficients so developed are used to transpose the consumptive-use data for a given area to other areas for which only climatological data are available.

As I said, several independent and related variables affect consumptive use. Of the climatic factors affecting plant growth, temperature and precipitation undoubtedly have the greatest influence. Furthermore, records of temperature and precipitation are far more universally available throughout the Western States than are data for other factors. The actual hours of sunshine also have an important part in the rate at which plants grow and consume water, but records of sunshine are not generally available. The theoretical daytime hours for each day are to be had for all the latitudes and may be used in place of the actual data. They may be misleading in areas where heavy fog or stormy weather exist during a large part of the year, but temperatures tend to correct for such a condition. Humidity records may also be used as a correction.

Disregarding the unmeasured factors, consumptive use varies with the temperature, daytime hours, and available moisture (precipitation, irrigation water, or natural ground water). By multiplying the mean monthly temperature (t) by the monthly percent of daytime hours of the year (p), there is obtained a monthly consumptive-use factor (f). It is assumed that the consumptive use (u) varies directly as this factor when a normal water supply is available.

Expressed mathematically, $U = KF =$ sum of kf, in which U is the consumptive use of crop (or evapotranspiration) in inches for any period; F is the sum of the monthly consumptive-use factors for the period (sum of the products of mean monthly temperature and monthly percentage of daytime hours of the year); K is the empirical coefficient (irrigation season or growing period); k is the monthly coefficient; and the other terms are as previously defined. The table shows the monthly percentages of daytime hours (p) for latitudes 24° to 50° N. (Page 344.)

The factor (F) for any period may be computed for areas in which monthly temperature records are available.

Percentages of Daytime Hours for Each Month of the Year for Latitudes 24° to 50° N.[1]

Mo	24°	26°	28°	30°	32°	34°	36°	38°	40°	42°	44°	46°	48°	50°
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
January	7.58	7.49	7.40	7.30	7.20	7.10	6.99	6.87	6.76	6.62	6.49	6.33	6.17	5.98
February	7.17	7.12	7.07	7.03	6.97	6.91	6.86	6.79	6.73	6.65	6.58	6.50	6.42	6.32
March	8.40	8.40	8.39	8.38	8.37	8.36	8.35	8.34	8.33	8.31	8.30	8.29	8.27	8.25
April	8.60	8.64	8.68	8.72	8.75	8.80	8.85	8.90	8.95	9.00	9.05	9.12	9.18	9.25
May	9.30	9.38	9.46	9.53	9.63	9.72	9.81	9.92	10.02	10.14	10.26	10.39	10.53	10.69
June	9.20	9.30	9.38	9.49	9.60	9.70	9.83	9.95	10.08	10.21	10.38	10.54	10.71	10.93
July	9.41	9.49	9.58	9.67	9.77	9.88	9.99	10.10	10.22	10.35	10.49	10.64	10.80	10.99
August	9.05	9.10	9.16	9.22	9.28	9.33	9.40	9.47	9.54	9.62	9.70	9.79	9.89	10.00
September	8.31	8.31	8.32	8.34	8.34	8.36	8.36	8.38	8.38	8.40	8.41	8.42	8.44	8.44
October	8.09	8.06	8.02	7.99	7.93	7.90	7.85	7.80	7.75	7.70	7.63	7.58	7.51	7.43
November	7.43	7.36	7.27	7.19	7.11	7.02	6.92	6.82	6.72	6.62	6.49	6.36	6.22	6.07
December	7.46	7.35	7.27	7.14	7.05	6.92	6.79	6.66	6.52	6.38	6.22	6.04	5.86	5.65

[1] Computed from "Sunshine Tables", U. S. Weather Bureau Bul. 805, 1905 ed. Abstract from SCS–TP–96 bulletin, *Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data*, by Harry F. Blaney and Wayne D. Criddle (1950).

Then by knowing the coefficient (K) for a particular crop in some locality, an estimate of the water use by the same crop in some other area may be made by application of equation U=KF. Computations of (K) from observed data for normal water supplies and growing seasons gave values for irrigated crops in arid and semiarid areas as follows: Alfalfa 0.85; corn 0.80; cotton 0.65; grass hay and pasture 0.75; citrus trees 0.60; deciduous trees 0.70; potatoes 0.75; rice 1.20; and vegetables 0.60. Those values should be reduced by about 10 percent for humid areas.

IRRIGATION EFFICIENCY is the percentage of irrigation water that is available for consumptive use by crops. When the water delivered is measured at the farm headgate it is called farm irrigation efficiency. When it is measured at the field or plot it may be designated as field irrigation efficiency.

The consumptive requirement of irrigation water depends on the amount of water consumed by the crops and also on the amount supplied by precipitation, winter soil-moisture carryover, and natural ground water contribution. After each of those factors is considered, the net amount of irrigation water that must be supplied for consumptive use of the crop can be determined. It is not the amount of irrigation water required for a farm or even a field, however, because the water cannot be applied without some loss, regardless of the method used.

Generally not more than 60 percent of the water delivered at the upper end of the farm is made available for the consumptive use of the crops. The balance is either lost in conveyance to the field, on the field itself through deep percolation, or through surface runoff from the field. Irrigation efficiencies must therefore be taken into account in estimating the irrigation water requirement of the crop. Efficiencies for different soil conditions and irrigation distribution systems range from 40 to 70 percent.

Computations of Rates of Consumptive Use for Crops in the Montrose Area, Colorado

Culture	*Growing season*	*Consumptive use factor (F)*	*Consumptive use coefficient (K)*	*Consumptive use (U)*	*U minus R*	
				Inches	*Inches*	*Feet*
Alfalfa	5/6–10/6	31.12	0.85	26.45	21.73	1.81
Grass hay	5/6–10/6	31.12	.75	23.34	18.62	55
Corn	5/6– 9/6	26.21	.75	19.66	16.02	33
Small grain	5/6– 8/6	19.83	.75	14.87	12.51	04
Orchards	5/6–10/6	31.12	.65	20.23	15.51	
Seeped land	5/6–10/6	31.12	.80	24.90	20.18	1.68
Natural vegetation	5/6–10/6	31.12	1.20	37.34	32.62	2.72

U=KF=Consumptive use for growing or irrigation season.
K=Empirical consumptive-use coefficient.
F=Sum of monthly consumptive-use factors (f) for the growing season.
R=Sum of monthly rainfall for growing season.

Illustration of the Method Used to Compute the Normal Seasonal Amount of Irrigation Water Required at Headgate at a Typical Farm, Montrose, Colo.

Classification and crop	*Area*	*Consumptive use minus rainfall (U−R)*	*Farm irrigation efficiency*	*Water required at farm headgate*	
				Unit	*Total*
Irrigated:	*Acres*	*Acre-feet per acre*	*Percent*	*Acre-feet per acre*	*Acre-feet*
Alfalfa	35	1.81	60	3.02	105.7
Grass hay	20	1.55	50	3.10	62.0
Corn	10	1.33	55	2.42	24.2
Orchard	10	1.29	60	2.15	21.5
Miscellaneous:					
Roads	3	0	....	....	0
Natural vegetation	1	2.72	....	2.72	2.7
Seeped lands	1	1.68	....	1.68	1.7
Total water delivery required at farm headgate for normal season	......	....	....	....	217.8

The irrigation water required to satisfy consumptive use by each crop growing or to be grown on a farm is obtained by subtracting the effective rainfall from consumptive water requirements during the growing or irrigation season. This net consumptive requirement (consumptive use minus precipitation) of the crop when divided by the farm-irrigation efficiency gives the seasonal amount of water required at the farm headgate for each acre of the crop. The sum of the requirements for each crop times its acreage gives the total amount of water that must be delivered to the farm headgate for satisfactory crop production. To this total must be added the amount of water needed for incidental farm operations.

The procedure and analysis of data for estimating irrigation requirements for a typical farm in Montrose area in Colorado are shown in the tables above.

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The Water Budget and Its Use in Irrigation

C. W. Thornthwaite and J. R. Mather

The purpose of irrigation is to counteract drought by making certain that the plants are not deprived of water at any time during their development. It is not possible to determine to what extent rainfall fails to supply the needs of plants for water without knowing their water requirements. Therefore the determination of the rates and the amounts of evaporation and transpiration from land surfaces under different types of cover in different parts of the country has been a research problem of major importance for a long time.

Scientists have tried various ways to determine the amount of water used by plants. One of the earliest attempts was to remove leaves or branches from a plant, let them dry for a brief time, and weigh them to see how much water they had lost. Another method is to place plants in sealed containers and measure the moisture that accumulates in the confined air. Experimenters have grown thousands of individual plants in pots, weighing them periodically to determine the evapotranspiration losses. These methods are highly artificial, and any generalizations from them sometimes have been greatly in error. In a German study, for example, transpiration from an oak woodland was computed as being more than eight times the total rainfall.

The only method so far developed that measures the evapotranspiration from a field or any other natural surface without disturbing the vegetation cover in any way is the so-called "vapor transfer" method. Water vapor, when it enters the atmosphere from the ground or from plants, is carried upward by the moving air in small eddies or bodies of air that are replaced by drier eddies from above.

We cannot see water vapor, but we can measure it in the air. We find that when evaporation is taking place the amount of moisture is greatest in the air near the ground and decreases with height above it. If we determine the rate at which the air near the ground is mixing with the air above it and at the same time measure the difference in water-vapor content at the two levels, we can determine both the rate and the amount of evapotranspiration. Furthermore, we can determine equally well the amount of water condensed as dew.

This method is not easy to understand or to use. It is hard to use because it requires physical measurements more precise than are usually made. Furthermore, the coefficient of turbulent transfer of air varies from time to time and from place to place. It even varies with height at a given time and place. Despite these difficulties, the method can be perfected and will answer many important questions for climatology and biology.

There are other ways of determining both water use and water need. Rainfall, water applied by irrigation, and water outflow are all measured in some irrigated areas. The fraction of water applied that does not run off is the evapotranspiration. In a few isolated places, mostly in the western United States, irrigation engineers have determined the evapotranspiration from plants growing in sunken tanks filled to ground level with soil in which water tables are maintained at different predetermined depths beneath the soil surface.

Increasing thought has been devoted since 1946 to the problem of measuring the water use of plants under always optimum conditions of soil moisture, and an instrument has been developed and standardized. It consists of a large soil tank so constructed that plants can be grown in it under essentially field conditions and can be provided with water as they need it. The tanks are 4 square meters in area and contain soil to a depth of approximately 70 centimeters. They have means for subirri-

gation from a supply tank designed so that actual amounts of water used can be accurately measured, or they can be irrigated by sprinkling from above. This latter method seems much more satisfactory in practice. When it rains, any excess water drains through the soil and is similarly measured. Thus every term in the hydrologic equation except evapotranspiration is measured. Evapotranspiration therefore can be determined as a difference. A number of these evapotranspirometers are in operation in widely scattered areas of the world, but many additional installations are needed if we are to understand the variation of evapotranspiration from one area to another.

From the various methods of determining evapotranspiration, imperfect and scattered though they may be, we get an idea of how much water is transpired and evaporated under different conditions. We find that the rate of evapotranspiration depends on five things: The climate, the supply of soil moisture, plant cover, the soil type and structure, and the land management. When the soil moisture is maintained at the optimum, land management and soil type or structure have little effect on the rate of evapotranspiration. Considerable evidence shows also that when the root zone of the soil is well supplied with water, the amount used by the vegetation depends more on the amount of solar energy received by the surface and the resultant temperature than on the kind of vegetation growing in the area. The water loss under optimum conditions of soil moisture, the potential evapotranspiration, thus appears to be determined principally by climatic conditions.

THREE POSSIBLE SOURCES of energy for evaporation or evapotranspiration are solar radiation, heat that reaches the evaporating surface from the air, and heat that is stored in the evaporating body. The latent heat of vaporization ranges from 574 cal/cc at 40° C. to 596 cal/cc at 0° C. If the heat needed for the evaporation of a small film of water came from the water itself, the water surface would be cooled well below the dewpoint. Thus, with no external source of energy, the surface temperature would quickly drop to the dewpoint of the air, and evaporation would cease. In an extensive body of deep water, evaporation could feed on the specific heat of the water for some time, but the process would cease long before much of the water had evaporated. Evaporation consequently can occur as a continuing process only while energy is being received from some outside source.

The sun is the original source of all energy that is involved in the transformation from liquid to water vapor. Not all of the energy received from the sun is used in evaporating water, however. Some of the incoming solar radiation is immediately reflected from the surface back to the sky. For a surface covered with vegetation, the reflected radiation may constitute about 25 percent of the total incoming. Also a certain percentage of the incoming radiation is radiated from the surface back to the sky; the amount depends on the temperature of the earth's surface and on the sky above. It is often between 10 and 15 percent of the incoming radiation.

After deducting the losses due to reflection and back radiation, the remainder (which is known as the net radiation) must be partitioned into three parts—one part heats the soil, one heats the air through contact with the soil surface, and one is utilized in evaporation.

In 1953, while participating in an Air Force field expedition to O'Neill, Nebr., the Laboratory of Climatology obtained an extensive series of micrometeorological measurements from which it is possible to compute the various components of the net radiation for a number of days. The computations show that when the soil is very moist more than 80 percent of the net radiation is used in evaporation. When the soil is dry, evaporation is greatly reduced, and most of the net radiation

Heat Used for Convection, Evaporation, and Storage in Soil, and Soil-Moisture Content on Different Days at O'Neill, Nebr., 1953

Date	Heat used for convection (C) (cal/cm²)	Heat stored in soil (S) (cal/cm²)	Heat used for evaporation (E) (cal/cm²)	Total C+S+E (cal/cm²)	E / C+S+E (%)	Soil moisture in 0–18'' profile (inches)
Aug. 13, 14	56.3	29.7	377.2	463.2	81	1.65
18, 19	59.1	−4.8	287.8	342.1	84	1.40
22	98.4	19.0	216.2	333.6	65	1.20
25	181.9	41.5	131.8	355.2	37	1.05
31	242.3	28.3	44.5	315.1	14	.75
Sept. 3, 4	121.1	−47.5	136.5	210.1	65	1.20

is devoted to heating the air, with very little remaining for evaporation. Between those extremes, the proportion of the net radiation that is spent on evaporation varies in a manner that has not been determined fully.

In the United States, the heat budget method of determining evaporation, which was originally suggested by W. Schmidt in 1915, was recognized as physically sound but was considered impractical because of the difficulty in obtaining the many necessary observations. Certain simplifying assumptions made it possible to compute evaporation from a lake or other large free water surface. But no way was found to determine the evapotranspiration from a land surface, where its rate is dependent on the amount of water in the soil.

This difficulty has been overcome by the introduction of the concept of potential evapotranspiration. When the soil moisture falls below field capacity, if the percentage of the net radiation utilized in the vaporization of water is proportional to the moisture in the soil, it is easy to determine the evapotranspiration from areas with varying amounts of soil moisture. Except for the fact that heat from the soil and from the air are additional sources of energy for evapotranspiration, it would be possible to determine the potential evapotranspiration directly from the net radiation.

Different types of vegetation differ in their potential evapotranspiration because they absorb different amounts of solar radiation. More incoming solar radiation is reflected back to the sky and less remains for heating and for evaporation as the albedo of a surface increases. (Albedo is the ratio which the light reflected from an unpolished surface bears to the total light falling on it.)

Anders Ångström has given the albedos of a few different surfaces as follows: Grass, 0.26; oak woodland, 0.175; and pine forest, 0.14. We have found that many of the common garden vegetables have albedos similar to that of grass. Potential evapotranspiration, from the three types of vegetation listed, should be least from the grass-covered surface and greatest from the pine-forest.

Considerable work must still be done in determining the exact contribution of each of the three sources of energy for evaporation under different conditions of climate, soil structure, and moisture. Because of these unknown factors and because observations of net radiation are very few and cannot yet be computed directly, it is still necessary to refer to other climatic data in order to determine the distribution of potential evapotranspiration.

THE MOST RELIABLE measurements of evaporation and transpiration that can be related to climatic factors in an effort to obtain a valid and practical relationship are based on the monthly or seasonal data from irrigation and drainage projects and on daily observations from carefully operated evapotranspirometer tanks. It has been found that, when the adjustments are

made for variations in day length, a close relation exists between mean temperature and potential evapotranspiration. Study of the available data has resulted in a formula that permits the computation of potential evapotranspiration for any place whose latitude is known and where temperature records are available. The formula is given in the preceding chapter.

Work is proceeding in several places toward the development of a new formula that is based on physical principles. In the meantime, the present empirical formula is being widely used in various studies of water balance.

Average annual potential evapotranspiration has been computed with this formula for some 3,500 Weather Bureau stations in the United States, and a map of the distribution of potential evapotranspiration has been prepared.

The average annual water need ranges from less than 18 inches in the high mountains of the West to more than 60 inches in three isolated areas in the deserts of Arizona and southern California. It is less than 21 inches along the Canadian border of the eastern United States and more than 48 inches in Florida and southern Texas.

The march of potential evapotranspiration follows a uniform pattern through the year in most of the United States. It is negligible in the winter months as far south as the Gulf Coastal Plain. It is only 2 inches a month in southern Florida. It rises in July to a maximum that ranges from 5 inches along the Canadian border to 7 inches on the gulf coast. In some mountain areas and along the Pacific coast, it does not reach 5 inches in any month.

The march of precipitation is highly variable from one region to another. In much of the United States more than half the rain falls in the growing season. In the Pacific Coast States the distribution is reversed; most of the rain falls in winter.

Since rainfall and evapotranspiration are due to different things, they are not often the same either in amount or in distribution through the year. In some places more rain falls month after month than the vegetation can use. The surplus moves through the ground and over it to form streams and rivers and flows back to the sea. In others, month after month, there is less water in the soil than the vegetation could use if it were available. There is no excess of rainfall and no runoff, except in places where the soil cannot absorb all the water as it falls. Consequently there are no permanent rivers and there is no drainage to the ocean. In still other areas the rainfall is deficient in one season and excessive in another, so that a period of drought is followed by one with runoff.

A FARMER who proposes to supply supplementary water to his crops must have some practical means of determining how much water to use and when it is needed. A common practice among farmers is to watch the plants for signs of moisture deficiency as a basis for supplying water. That is not satisfactory, because by the time the plants begin to show some signs of water need they are already suffering, and the yield has been reduced correspondingly.

Instead of watching the crop for indications of drought, some investigators suggest watching the soil. One investigator has stated that the only known way to be sure that soil moisture is present in readily available form is by frequent examination of the subsoil by the use of a soil auger or similar tool. Several devices have been developed to be installed permanently in the soil to give a continuous indication of the amount of moisture remaining. Among these devices are elements made of gypsum, fiber glass, and nylon in which the electrical resistance varies with moisture. Many of these blocks have been used in some of the large irrigation enterprises to determine the time to apply water. Details about them are given on pages 362–371.

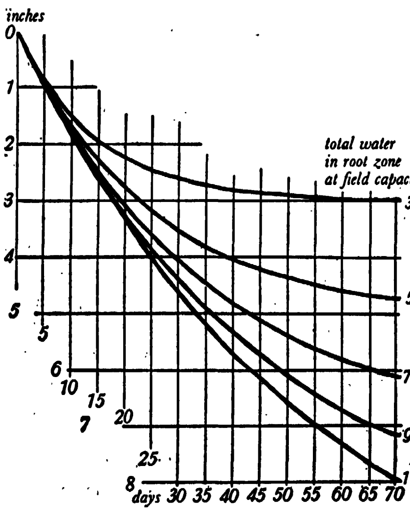
The climatological approach is different. The moisture in the soil is regarded as being a balance between

what enters it as a result of precipitation and what leaves through evaporation and transpiration. Precipitation is easily measured by means of raingages, and good farmers regularly keep account of it. It is not easy to measure evapotranspiration, but the research we described provides a way to determine it. Consequently we can determine the daily moisture loss from the soil through evapotranspiration and can compare it with the daily rainfall. An irrigation schedule thus can be set up as a bookkeeping procedure. The moisture in the soil may be regarded as a bank account. Precipitation adds to the account; evapotranspiration withdraws from it. We merely need to keep track of the evapotranspiration and restore by irrigation whatever is not promptly returned by precipitation.

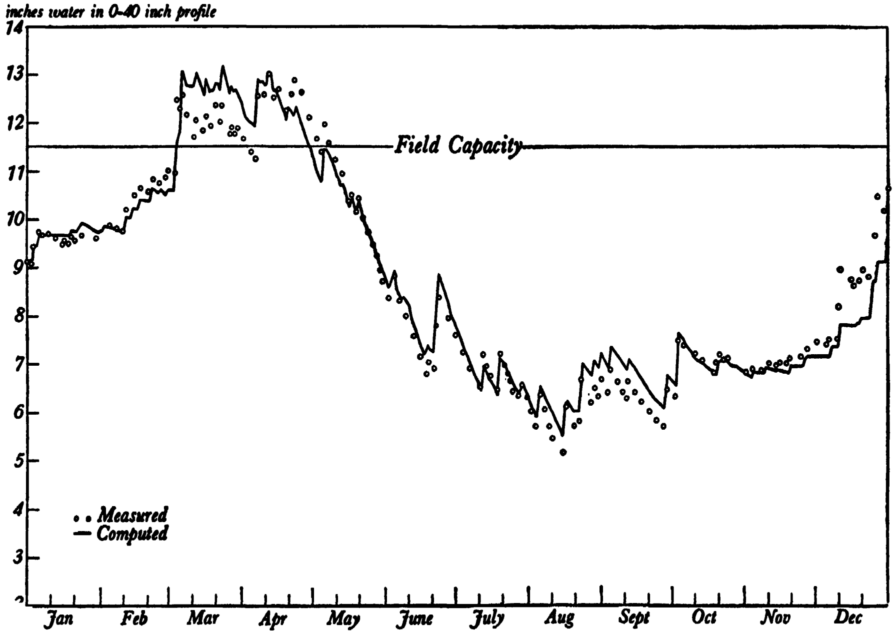
When the moisture content of the soil is at field capacity or above, any water that is added to it by precipitation is lost by downward percolation. This gravitational water is detained only briefly, the period depending on the permeability of the soil and the amount of the gravitational water. When the soil moisture is below field capacity, precipitation first brings the soil moisture storage up to that level. The amount of water that can be stored in the root zone of the soil depends on its depth and on the soil type and structure. With shallow-rooted crops on a sandy soil, only 1 to 2 inches of water can be stored for free use of the plants. With deep-rooted crops on a fine-textured soil, as much as 6 to 8 inches of water will be readily available. The amount of water that can be held as storage must be determined from a consideration of the soil and crop in each instance.

In computing the depth of water in a soil column, we must consider separately the gravitational water and the capillary water. At field capacity, the soil contains no surplus of gravitational water and no deficit of capillary water. Thus field capacity becomes an important point in the computation.

Evaporation from a moist soil begins immediately to lower the moisture content of the soil. As the soil dries, the rate of evapotranspiration diminishes. Evapotranspiration at first goes on at nearly the maximum rate from all soils, but by the time 1 inch of water has been removed the rates from different soils begin to differ. When one-half of the water is gone, the rate of evapotranspiration falls to one-half of the potential rate, and plants begin to suffer from drought. With a constant rate of potential evapotranspiration of 0.2 in/day, the half-rate would be reached after 7 days in coarse sand but not until after 37 days in fine-textured soil. Within 20 days the soil moisture in coarse sand would be reduced to a point where the evapotranspiration is only 25 percent of the potential rate. Long before that much water has been lost, the plants are suffering severely from lack of water, and growth is seriously retarded. In soil that can store 11 inches of water, this same degree of drought would be reached only after 75 days. Tables have been prepared for making the computations. They give the daily rates of soil moisture deple-



This sketch shows actual rate of soil moisture depletion from soils holding different amounts of water in the root zone, assuming a constant rate of potential evapotranspiration of .2 inch a day.



Soil moisture in 0–40'' profile on Watershed Y102, Coshocton, Ohio, 1944. Measured values obtained by Soil Conservation Service from soil samples and by use of weighing lysimeter. Computed values are from daily climatological data; the water budget method was used.

tion under varying rates of evapotranspiration for soils holding different amounts of water at field capacity.

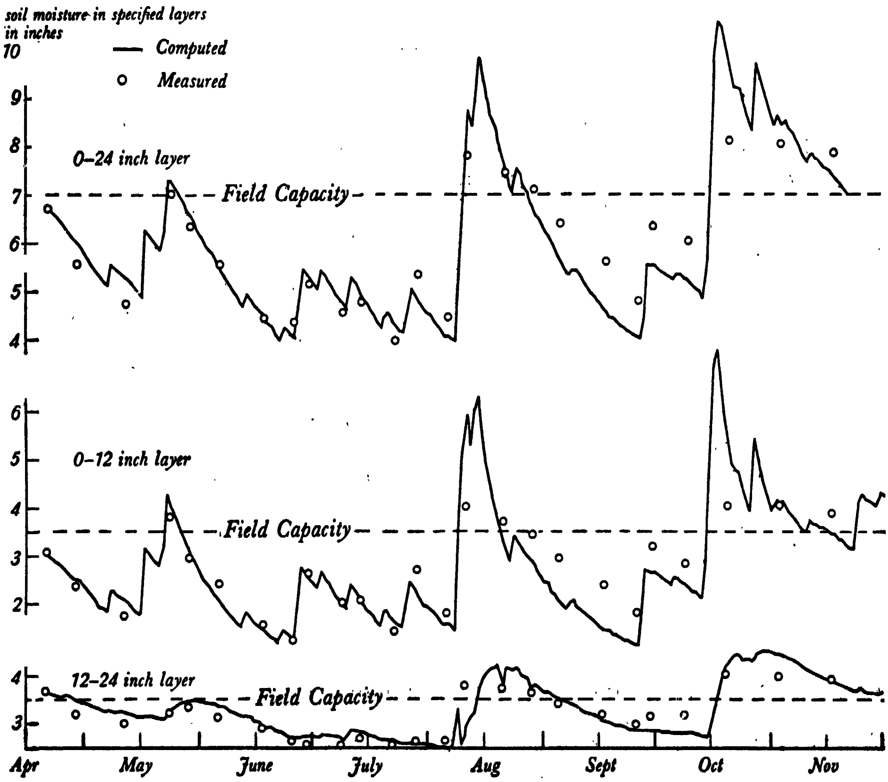
On the basis of the concepts we have outlined, the day-to-day variations in soil moisture have been worked out for several places in the United States. The results have been compared with actual soil moisture determinations. Considering the assumptions and approximations made in computing soil moisture on the one hand and the methods of soil sampling employed on the other, close agreement has been found between the measured and computed values of soil moisture.

In making the computations for other localities with different types of soil and for root zones of different depths, we must use the appropriate rate of soil moisture depletion determined for the particular amount of water held in the considered depth of soil at field capacity. Thus we can compute the trend of soil moisture in any type of soil and for a soil layer of any desired thickness. Furthermore, the water regimes of individual layers of the soil profile can be determined separately from the climatic data.

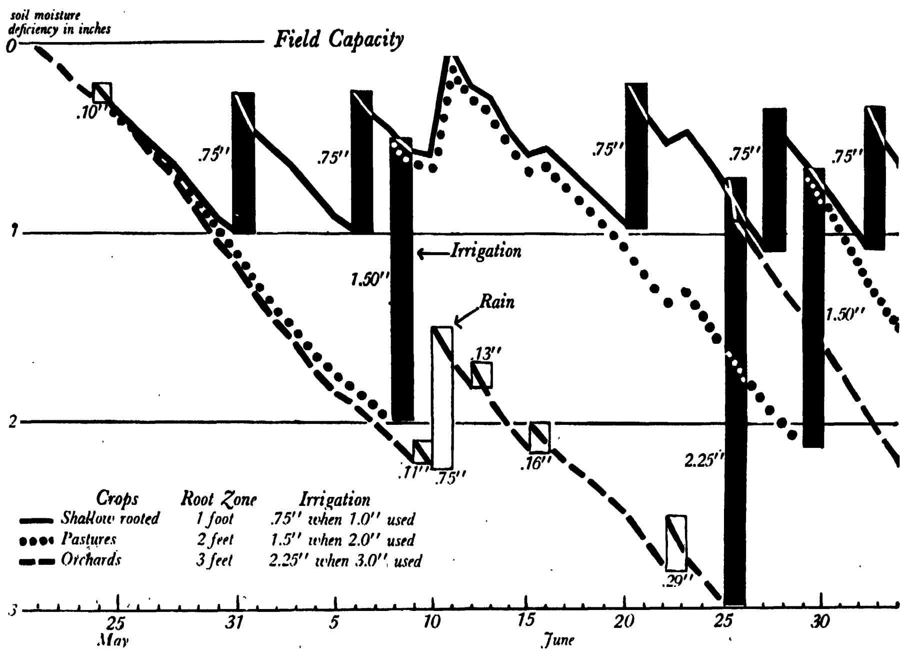
Computations for a number of places and for different years support the conclusion that soil moisture can be determined with all needed precision from climatological data. It is apparent from the agreement found between measured and computed values that the climatological approach will permit the accurate determination of the movement of water through soils and the amount of storage in any selected layer in the soil. It is still necessary, however, to make certain assumptions in order to obtain the computed values. Further work should make it possible to refine the method and to base it on sound physical principles.

An irrigation schedule is a natural outgrowth of this method of computing soil moisture. One can set up limits below which the soil moisture will not be allowed to fall for the particular crop and depth of root zone in question. Then, by keeping daily account of how much water has been lost from the soil, we could know exactly when the predetermined level of soil moisture depletion is reached and to know just how much to irrigate to bring the moisture level back to a safe value. Shallow-rooted crops will have to be irrigated more frequently but with smaller amounts of water than will deeper-rooted pastures or orchards. If irrigation is scheduled by keeping continuous account of the soil moisture, no great moisture deficiency can develop in the soil to limit growth and there will be no overirrigation to damage both soil and crop and to result in a wasteful misuse of water.

Sometimes it is not necessary or desirable to make detailed daily computations of deficiency of soil moisture. For instance: A basic problem in agriculture is to determine the intensity and frequency of drought as a step in the evaluation of the economic feasibility of irrigation. To make a quantitative determination of drought intensity, it is necessary to have records of soil moisture deficiency, while to determine drought frequency, soil moisture records for a long series of years are needed. In this case the precision that can be gained by using daily



Soil moisture in specified layers of soil profile, College Park, Md., 1942. Measured values obtained by Soil Conservation Service from soil samples. The values were computed from daily climatological data, the water budget method was used.



This sketch shows the irrigation schedule for three different types of crops, in Seabrook, N. J., 1954. Soil holds 3 inches of water at field capacity per foot depth of soil. Rain on May 21 brought soil up to field capacity so that computations of deficiency start from 0 on that day.

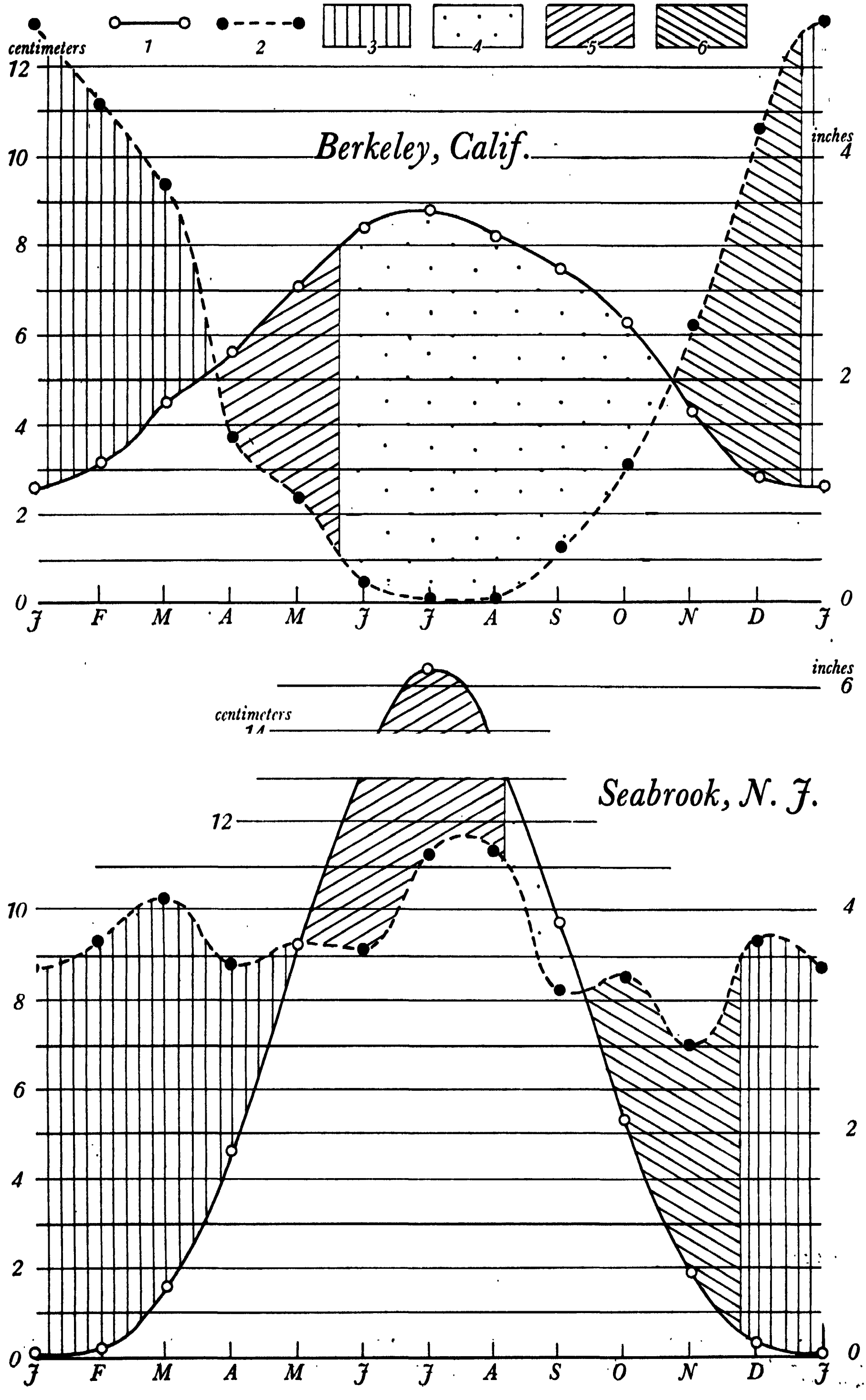
climatological values for computing soil moisture deficiency is not warranted. It would be more satisfactory to use monthly means of temperature and precipitation and to determine moisture deficiency with perhaps less accuracy but for more years of record and for a greater number of stations than would otherwise be possible.

In using monthly instead of daily values of climatic factors, certain of the procedures employed in the daily computations can be generalized. For example, although it is recognized that the amount of water in the root zone available to plants will vary with soil structure from about 1 inch on shallow soils to about 6 to 8 inches on deep, well-aerated, silt loam, in normal agricultural soils the total amount of water available to plants is far less variable than conventional studies of soil moisture would indicate. A satisfactory average has been found to be 4 inches.

Gravitational water can be easily handled in the monthly computations, since it is possible to consider surface runoff and the percolation of gravitational water as one quantity, runoff. It is not necessary to employ any daily factor for the detention of gravitational water in the profile but merely a general monthly detention factor for all runoff, a factor that varies with the size of the watersheds and is about 50 percent for large watersheds.

Using these more general assumptions, we can compare the monthly march of precipitation and potential evapotranspiration at different places.

At Seabrook, N. J., the potential evapotranspiration is negligibly small in winter, but in early spring it begins a rapid rise, which reaches the high point of the year of more than 6 inches in July. It falls rapidly in autumn. The corresponding precipitation is far more uniformly distributed throughout the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year, being very close to 3.5 inches in 9 of the 12 months. The rainiest months are July and August, each of which receives about 4.5 inches; November, the driest month, has only 2.75 inches.

In this example, rainfall and water need do not coincide. There is too much rain in winter and too little in summer. Thus at the time of maximum rainfall in July and August there is a water deficiency, but in November, when rainfall drops to the lowest value of the year, there is a water surplus. Water need falls below precipitation in early autumn. For a while the surplus rainfall replaces soil moisture that had been used up previously. From then on, the surplus water raises ground water levels and produces surface and subsurface runoff. Both transpiration and evaporation increase rapidly in spring, and soon water need surpasses precipitation. When the soil moisture is at field capacity, actual and potential evapotranspiration are the same and all precipitation in excess of the potential evapotranspiration is realized as water surplus. When precipitation does not equal potential evapotranspiration, the difference is made up in part from soil moisture storage; but as the soil becomes drier the part not made up is larger. This is the water deficit, the amount by which actual and potential evapotranspiration differ.

Both water surplus and water deficit can be derived from the comparison of the monthly precipitation with the monthly potential evapotranspiration. The water surplus occurs in winter in Seabrook and amounts to about 15 inches, and the water deficit occurs in summer and amounts to about 1 inch. Through the course of the year there is a net water surplus amounting to 14 inches. This system of monthly water bookkeeping makes it possible also to determine the water that must be accounted for as the soil moisture storage.

In Berkeley, Calif., in a different climatic zone, nearly all the rainfall comes in winter and almost none in summer. Here the winter water surplus is 4 inches and the summer water deficit of 7 inches therefore are both comparatively large.

Both rainfall and potential evapotranspiration vary from one year to another. Thus conclusions based on longtime averages tell only a partial story. Even a very rainy place may occasionally experience drought. The length and severity of summer drought in Seabrook and Berkeley vary greatly from year to year.

To determine how severe drought may be in a place, we must compare water need with water supply in individual years. In that way we can determine how often water deficiencies of various amounts take place. As an example we may consider selected moisture data obtained during the 25-year period, 1920–44, at four stations in agricultural areas of the United States: Hays, Kans.; Charles City, Iowa; Wooster, Ohio; and Auburn, Ala.

In Hays, the least rainy station, the average rainfall is about 22 inches. In Auburn, the rainiest, it is about 50 inches. The average rainfall in Hays is about 10 inches less than the need; in Auburn it is 10 inches greater. In Auburn, however, much of the rainfall comes in winter, when it is not needed. It becomes surplus water and flows away. In the summer, however, water deficiency is large. Water deficiency in Hays also is large, ranging from nearly 20 inches to about 2 inches. In Hays there is not enough rainfall; in Auburn there is more than enough, but it is badly distributed through the year.

In both Charles City and Wooster, with a better distribution of rainfall

Average march of potential evapotranspiration (1) and precipitation (2) through the year at Berkeley, Calif., and Seabrook, N. J. Diagrams also show other factors of the moisture balance: Water surplus (3); water deficit (4); soil water utilization (5); and soil water recharge (6).

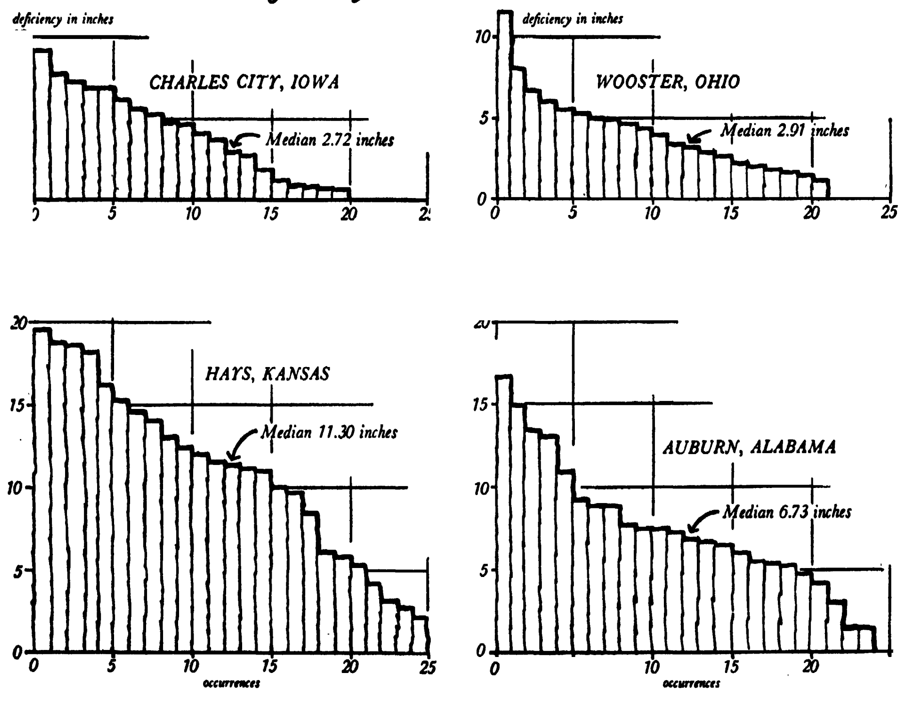
Comparative Moisture Data at Selected Stations in the United States—Median Values of the 25-year Period 1920–1944

Station	Precipitation (inches)	Potential evapotranspiration (inches)	Actual evapotranspiration (inches)	Water surplus (inches)	Water deficiency (inches)
Hays, Kans.	22.13	31.26	21.02	0.00	11.30
Charles City, Iowa	30.94	25.91	23.19	8.90	2.72
Wooster, Ohio	35.63	26.46	23.82	11.26	2.91
Auburn, Ala.	49.84	39.45	33.07	18.43	6.73

through the year, the water deficiencies are smaller, being less than 1 inch and 3 inches, respectively, in half of the years of record. Drought intensity and frequency are a little smaller in Charles City than in Wooster. There is also a lower water surplus in Charles City—8.90 inches, compared with 11.26 inches. Thus, of the four stations, Charles City most nearly approaches the ideal climate for agriculture, for its water supply most nearly coincides with water need.

MANY STATISTICAL STUDIES of drought have been made, but almost without exception they are mere tabulations of days receiving less than a specified amount of rain. For example, in a probability analysis of drought in the United States, published in 1942, a drought period was defined as one in which not more than 0.10 inch of precipitation occurred in any consecutive 48 hours. In 1946 the drought periods of six Georgia stations were tabulated, drought being defined as "a period of

Annual Water Deficiency at Selected Stations, 1920–1944



14 days or more in which there is not one-quarter of an inch of rainfall in any one 24-hour period." A suggestion was made in 1954 that punched cards of the Weather Bureau be used to tabulate the number of days without rain during the growing seasons at various places in the last 20 years. The tabulations "would yield the basis for saying that in July, 3 years out of 5 will get one dry spell which will last 18 or more days." Such tabulations, it was thought, would enable agricultural engineers and others to tell farmers whether they should invest in irrigation equipment.

Such tabulations of the number of days without rain actually do not give information about drought: We cannot define drought only as a shortage of rainfall, because such a definition would fail to take into account the amount of water needed. Furthermore, the effect of a shortage of rainfall depends on whether the soil is moist or dry at the beginning of the period.

H. L. Shantz explained that drought in its proper sense is related to soil moisture and that it begins when the available soil moisture is diminished so that the vegetation can no longer absorb water from the soil rapidly enough to replace that lost to the air by transpiration. Drought does not begin when rain ceases but rather only when plant roots can no longer obtain moisture in needed amounts.

Differences in average yields in different localities are proportional to differences in drought incidence. The farmers of the East and Southeast get low returns from their work on the land partly because of high drought incidence resulting from the lack of coincidence between rainfall and water need. During much of the growing season, the soil does not contain enough moisture, and in the nongrowing season a large water surplus impoverishes the soil by leaching.

To farmers everywhere drought is a serious matter. Drought is hard to measure because we are not yet able to determine the water needs of plants very accurately. We do not know when to expect droughts or how intense they may be. Therefore we cannot be sure which moisture-conservation measures may be best at a given time and place. Droughts deserve study. Not until we have conquered drought by scientific irrigation will we achieve the maximum production from the soil.

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Soil Moisture in Relation to Plant Growth

Cecil H. Wadleigh

Growing plants transpire enormous quantities of water which they take from the soil. One cornfield in Iowa transpires enough water during a season to cover the field to a depth of 12 or 16 inches. The production of 1 ton of dry alfalfa hay on the Great Plains may involve the transpiration of 700 tons of water—more or less, depending on the evaporating power of the atmosphere. At a temperature of 75° F. and a relative humidity of 50 percent, a tensional force of approximately 1,000 atmospheres would have to be applied to water to stop evaporation.

Plants lose water continuously. The lowest loss is at night and the highest at midday. But often the soil water is not replenished by rain or irrigation over periods of weeks or months. Hence the soil acts as a moisture reservoir for the plants.

To a Colorado wheat grower, who may harvest 50 bushels an acre or nothing, according to the status of the moisture reservoir in his soil in a given season, it would be difficult to overemphasize the importance of soil moisture in plant growth.

The capacity of the soil moisture reservoir is limited by the field capacity (upper limit) and the permanent wilting percentage (lower limit) of the soil in the effective root zone of a crop. Field capacity is the moisture percentage of a soil, expressed on dry-weight basis, in the field 2 or 3 days after a thorough wetting of the soil profile by rain or irrigation water. Permanent wilting percentage is the moisture percentage of soil at which plants wilt and fail to recover turgidity. It is usually determined by growing dwarf sunflower plants in small containers of the soil under examination. The moisture held by the soil against a displacing

force of 15 atmospheres (221 pounds a square inch) is a good estimate of the permanent wilting percentage.

There is a wide disparity between the value of 1,000 atmospheres associated with the evaporating power of the air on a warm, dry day and the 15 atmospheres of soil moisture tension associated with the wilting of plants. Rate of entry of water into the roots is impaired by the prevalence of only a few atmospheres of soil moisture stress, even though the plant can withstand a great drying force at the leaf surfaces.

The permanent wilting percentage of soils may vary from 3 percent for a coarse sandy soil to 23 percent for a fine clay. Comparable figures for the range in field capacity are 8 and 40 percent.

F. J. Veihmeyer and A. H. Hendrickson, of the California Agricultural Experiment Station, have conducted extensive experiments demonstrating the usefulness of these two soil moisture constants in irrigation practice. They designate the moisture held by a soil in the range between field capacity and permanent wilting percentage as the available range. Thus the moisture reservoir constitutes the water in the available range held by the mass of soil in the active root zone.

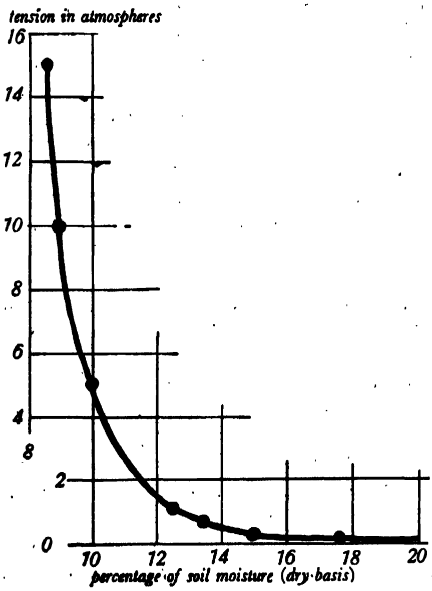
Let us examine the amount of water that may be available in a unit volume of soil, say, 1 cubic foot. A mineral soil is made up of three major components, air, water, and mineral particles. One cubic foot in the dry state will weigh from 65 pounds for clays to 110 pounds for sands. Soil particles have an average density of 2.65, and a cubic foot of soil minerals would weigh 165 pounds. Thus, as much as 60 percent of the volume of a clay soil may be voids filled with air and water. In coarse sands it may be as low as 30 percent.

It is essential for most plants that the voids be only partially filled with water in order to provide necessary aeration.

Plants vary markedly as to rooting habit under favorable soil conditions. Roots of lettuce and spinach penetrate only 12 to 15 inches; those of potatoes and peas, about 2 feet; tomatoes and tobacco, 3 feet; field corn and asparagus, 4 feet; and alfalfa and grapes, down to 8 or 10 feet or more. Potatoes growing in a loam that can hold 1.5 inches of available water per foot of depth would have a total moisture reservoir of 3 inches of water—enough for a vigorously growing potato crop for about 1 to 3 weeks, depending on the evaporation rate.

THERE IS EVIDENCE that the water in the available range of a soil is held equally available to crop plants, even though water at the upper limit, field capacity, is withheld from the plant roots by a tensional force of about only 1.5 pounds a square inch; whereas water at the lower limit, permanent wilting percentage, is withheld by a tensional force of about 200 pounds a square inch. Those values constitute a wide range in tensional force. Why, then, do we find evidence that insofar as plant growth is concerned water is equally available between those limits?

The relationship between soil moisture tension and moisture content provides an answer:



This chart shows the relationship between soil moisture content and tension in Panoche loam.

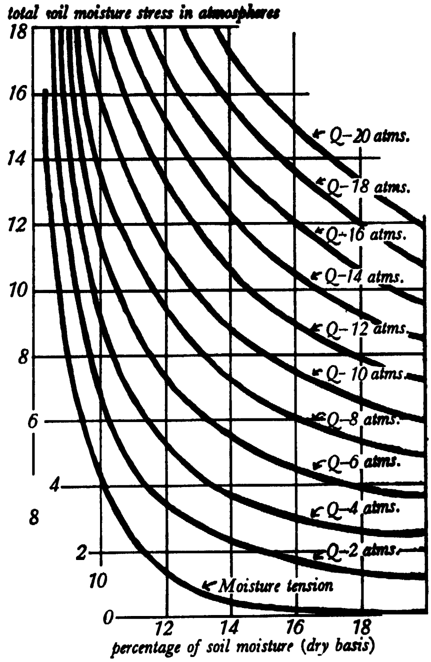
These data were taken on a sample of Panoche loam, a soil found in California. This soil has a field capacity of 18 percent and a permanent wilting percentage of 8.6 percent. It is of key importance to note that the change in moisture tension with a moisture content between these two moisture percentages is not linear, but markedly curvilinear. As the soil dries out toward the permanent wilting percentage, there is but little increase in moisture tension even when two-thirds of the available moisture has been used up. On the other hand, as the permanent wilting percentage is approached, there is an enormous increase in moisture tension associated with a small decrease in moisture content. Thus the shape of the curve explains why there is evidence indicating that, for practical purposes, soil water is essentially equally available almost down to the wilting percentage. Contrary evidence is also prevalent. In general, when two-thirds to three-fourths of the available water has been exhausted from the moisture reservoir, plants may stop growing.

All soils have moisture retention curves similar to the one in the chart, but the shape and locus vary.

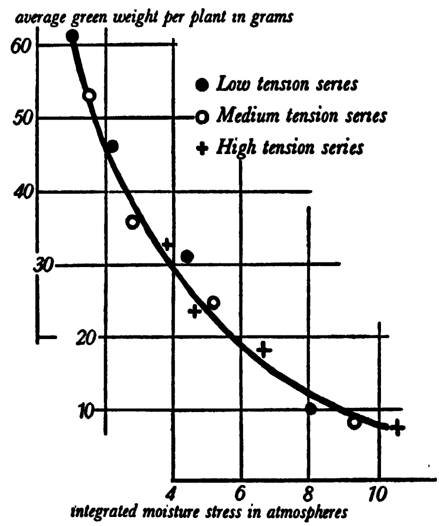
Dissolved salts derived from fertilizers or from natural sources, as in saline soils, also impair the availability of water to plants. Dissolved salts increase the osmotic pressure of a solution, which is measured in terms of atmospheres, as soil moisture tension may be. There is evidence that the effects of moisture tension and osmotic pressure are additive in impeding water availability to roots. The sum of these two forces has been called the total soil moisture stress.

The second chart shows the effects of various levels of added salts, expressed in atmospheres of osmotic pressure, on the total soil moisture stress of the soil having the tension curve shown in the first chart. Increased levels (Q values) of added salts decrease the availability of soil water.

An experiment exemplifying the lat-



The relationship between total soil moisture stress and moisture content of a Panoche loam with various increments in osmotic pressure of the soil solution induced by added salt.



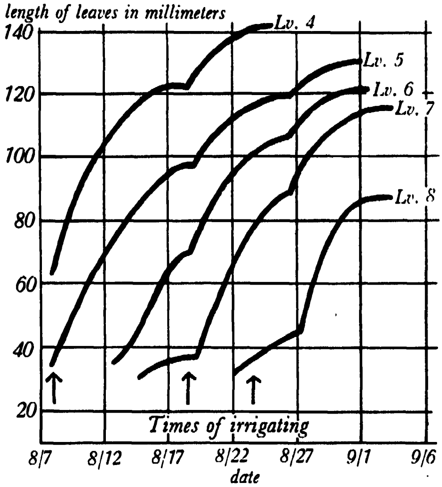
Accumulated growth of bean plants as related to total soil moisture stress arising from various combinations of moisture tension and osmotic pressure.

ter statement is illustrated by the data in the third chart. Cotton plants were grown in oil drums filled with soil to which 0.1 percent of sodium chloride was added to make it slightly saline. (Q equalled about 6 atmospheres at 12 percent moisture.) The moisture content of the soil was determined daily by weighing the drums, and the length of each leaf was measured at 8 o'clock every morning. When 90 percent of the theoretical amount of available water was exhausted, the soil was irrigated, as shown by the arrows. Nearly every leaf stopped growing a day or two prior to the irrigations, even though the plants did not wilt. Calculations revealed that the total soil moisture stress associated with complete cessation of leaf growth was 14 atmospheres.

The foregoing effects on diurnal leaf growth are additive through time. This is further shown by the data presented in the chart, (page 360) showing the total soil moisture stress on bean plants grown to maturity in soil contained in oil drums and varying as to salinity (osmotic pressure effect) by adding 0, 0.1, 0.2, and 0.4 percent sodium chloride to different batches of the soil used. Some of the soil cultures were kept quite moist (low tension series); others were irrigated when two-thirds of the available water was used (medium tension series); and others were allowed to dry down almost to the wilting percentage (high tension series). Growth of the bean plants was closely related to total soil moisture stress, regardless of whether the stress arose from salinity or moisture tension.

Plant growth is primarily the result of two major processes: Cell division (production of new cells) and cell enlargement. Intensive investigations on sugar beets by D. J. Watson of the Rothamsted Experimental Station in England indicated that soil moisture deficits affect growth mainly by inhibiting cell enlargement, rather than by affecting cell division.

A plant cell is a living osmometer in



Growth of leaves of a cotton plant as related to soil moisture depletion and replenishment.

which the contained solution tends to absorb water from its surroundings, thereby effecting an internal hydrostatic pressure on the cell wall—turgor pressure. This turgor pressure is the force that brings about cell enlargement, and its effectiveness is controlled by the action of a substance within the cell known as auxin. Thus, the plant growth is directly related to degree and duration of turgescence of plant tissues.

Water loss from plants by transpiration brings about a tensional stress within the plant that is counteractive to the prevalence of turgor pressures in expanding cells. This internal tensional stress is eased by water absorbed from the soil. Conditions such as poor soil aeration, high moisture tension, or salinity may impair the capacity of roots to absorb water so that moisture tension in the plant is not adequately alleviated. This may reach the state where the plants lose turgidity.

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How To Measure the Moisture in the Soil

Howard R. Haise

Farmers, agronomists, engineers, hydrologists, and others have needed a practical way to measure soil moisture quickly and accurately without having to do the costly and tedious work of "pulling a mile or two" of soil samples.

They need data on soil moisture for studies of runoff in watersheds, the effect of the accumulation of moisture under pavements, the movement of moisture in the soil, the availability of moisture for plant use, the time and amount of irrigation, and many other problems.

From the standpoint of agronomists, two factors are involved in measuring day-to-day changes of soil water—the amount of water per unit mass or volume of soil, or percentage of moisture; and the energy or force with which water is retained.

Percentage of moisture, as determined by oven drying, represents the total water content of a soil. In terms of plant growth, it includes unavailable and available water. Unavailable water includes the portion held so firmly by the soil that it cannot be absorbed by plant roots.

Available water is usually considered the amount retained between so-called "field capacity," or the moisture content found 2 or 3 days after a soil has been wetted to a depth of at least 3 feet, and the permanent wilting percentage, or that moisture content at which plants cease to grow. Strictly speaking, free water that moves downward by gravity in the 2 or 3 days after rainfall or irrigation is also available. The amount of water supplied to plants during this interval is appreciable and cannot be ignored—particularly in soils that do not have a field capacity. As the available moisture merits prime consideration, any method that measures the water status of a soil must be capable of detecting day-to-day changes within this moisture range.

Methods of measuring soil water are of various kinds:

Methods based upon gravimetric measurements: (*a*) Determination of moisture in soil samples; (*b*) determination of moisture in porous media in moisture equilibrium with soil water.

Methods that depend on the measurement of equilibrium tension between water in a porous ceramic cup and the soil water.

Methods that depend on the electrical properties of soil or porous media in moisture equilibrium with soil water: (*a*) Conductance or resistance methods; (*b*) capacitance methods; (*c*) dielectric methods.

Methods based on thermal properties of soil or porous media in moisture equilibrium with the soil water.

Methods that depend on neutron scattering.

Methods that depend on the resistance of soil to penetration.

The gravimetric method, notwithstanding its shortcomings, is the most accurate method now available. The standard procedure requires removal of soil samples in the field with a soil tube or auger. The moist soil is transferred to a closed container and weighed. The container is then opened, placed in an oven, and dried at 105° C.

The soil sample is reweighed when it has reached constant weight. The loss in weight represents soil water expressed as a percentage of dry soil. If the bulk density of a field sample is known, the amount of water can be expressed as a percentage of the bulk volume or in depth of water per unit of soil depth. The use of the information to determine when irrigation is needed and how much water to apply makes it important that the upper and lower limits of available water be known—that is, the field capacity and permanent wilting percentage. Those values can be obtained by standard field and laboratory procedures.

The practical disadvantages of using

gravimetric methods in general moisture studies are many. It takes at least 24 hours to obtain results. Considerable labor, time, and equipment are necessary to sample the soil, dry it, and make weighings and computations.

Gravimetric sorption blocks, developed in 1942 by W. E. Davis and C. S. Slater, are made of Hydrocal, a gypsum product, and consist of a porous, truncated outer chamber, or casing, containing a closely fitted tapered porous plug. Sized sand is placed in the porous plug to provide sensitivity in the range of moisture near field capacity. The unit is secured to a bakolite lift tube long enough to be installed at the desired soil depth. When it is buried in moist soil, the sorption of moisture by the porous material occurs until equilibrium with soil water is attained. Correlation between the weight of porous plug and moisture in the soil gives an indirect measure of the soil moisture. A wire hook is used to remove the porous plug through the lift tube for weighing on a torsion balance. Separate calibration curves are required for each individual soil.

Gravimetric sorption blocks provide a sound basis for measuring soil moisture, but the method has not become widely used by research workers, technicians, or farmers. Its main disadvantages appear to be a lack of a suitable device to weigh porous plug; a lag in approaching moisture equilibrium; the deterioration of gypsum, especially under waterlogged conditions; and lack of durability. The unit, however, is not affected by salts in soil.

L. A. Richards and A. R. Weaver, working at the United States Salinity Laboratory, developed a sorption block soil moisture meter similar in principle to the one just described. The instrument uses a sorption block of 90 percent porous brick and 10 percent diatomaceous earth, and is more durable than gypsum. The block is covered with a thin sheet of mica and placed on long-fiber asbestos paper in contact with soil. A rubber stopper attached to a metal tube holds the disk in place and seals the sorption block chamber. This assembly is clamped into position within a larger metal tube and can be raised to free the porous disk for weighing. A portable Jolly balance mounted on the outer metal tube is used for weighing the sorption block. A wire suspends it for weighing.

Sorption block moisture meters provide the advantages of a durable sorption disk; accurate readings, even with long periods of neglect and lapse of time; and no adverse salt effects. The main disadvantage is the fragile character of the balance needed for accurate weighings, a factor that has limited the wider use of the device.

A soil-moisture tensiometer, developed by Dr. Richards and his associates, measures tension or condition of water in soil. It consists of a porous cup filled with water and attached to a vacuum gage or mercury manometer. Tension values are usually expressed in centimeters of water or mercury and indicate availability of soil water to plants. When the relationship between soil moisture tension and soil water is known, instruments can also be used to indicate the moisture content of a soil. The instruments have been made in forms to suit various needs. The type that utilizes a mercury manometer is usually preferred as a research tool because it affords greater precision. Tensiometers equipped with Bourdon vacuum gages are better suited for practical applications of irrigation control because of their simplicity. They are manufactured in various forms.

A simplified version of a tensiometer is shown on page 370. When it is filled with water and buried in moist soil, an outward movement of water occurs through the porous cup to establish moisture equilibrium between water in the cup and the soil water. Increases in tension that occur as the soil dries cause the vacuum gage readings to increase. Conversely, an increase in soil water content reduces tension and lowers the gage reading. The tensiometer continues to record fluctuations in soil water content if a tension of ap-

proximately 0.85 atmospheres is not exceeded. That is made possible by selecting a ceramic with pores small enough so that, when it is filled with water, air cannot enter the system. When tension of the soil water exceeds 0.85 atmosphere, however, air enters the system, and the instrument ceases to function. When soil water has been replenished by irrigation or rainfall, the instrument must again be filled with water before it can operate.

Some experience is required to use tensiometers. Unreliable results can be expected if air enters the unit through leaks developing at rubber connections. Neoprene and Koroseal tubing is used in preference to ordinary rubber tubing because it is less permeable to air and will not deteriorate rapidly in direct sunlight. Furthermore, ordinary rubber tubing in contact with brass or copper tubing will form copper sulfide, which destroys the seal.

Faulty cups can also be a source of air leaks in the system. The bubbling pressure can be determined by observing the pressure at which leaks occur when the walls of the ceramic cup are saturated and immersed in water. Cups so tested should withstand a pressure of 15 pounds per square inch or greater. Air leaks will sometimes develop at the contact point of setscrews used to secure the porous cup to the metal tensiometer support. Setscrews should not be tightened more than necessary to hold the cup in its mounting when the tensiometer is removed from the soil. Setscrews have been eliminated in newer models.

Dissolved air released from water under a vacuum pressure is collected in an air trap visible above the ground surface. The presence of air in the trap indicates that the instrument should be serviced. The opening provided by the air trap also permits addition of water to the system. Distilled water, freshly boiled to remove dissolved air, should be used. The use of an ear syringe is convenient to fill the unit and flush air from the system. Pressure applied to the syringe after the air trap has been filled forces water through the capillary tube connecting the porous cup to the mercury manometer. Exclusion of air is substantially complete when air bubbles no longer are visible as water flows through the capillary glass tubing of the manometer. Water should not be added under pressure to units equipped with vacuum gages, as the Bourdon spring can be damaged easily. It is preferable to apply a vacuum to the water system with a bicycle pump in which the valves have been reversed. This arrangement can also be used on the mercury-type tensiometer.

Day-to-day fluctuations in tensiometer readings due to temperature change have been observed on coarse-textured soils in deserts. The phenomenon is associated with the transfer of vapor and results from a temperature gradient between the porous cup and soil. When daytime temperatures rise, heat conducted through the metal tensiometer support warms the porous cup. The result is a temperature gradient in the direction of the cup. Vapor transfer from cup to soil causes the mercury manometer to rise. Conversely, a drop in temperature at night lowers the temperature of the cup below that of the soil and causes free water to collect at the soil-cup interface, much the same as a glass filled with ice water collects moisture on a humid day. As water moves into the cup, tension in the system is lowered and the mercury in the manometer drops.

The magnitude of the fluctuations depends upon soil, soil depth, climatic conditions, and the type of tensiometer and materials used in its construction. On coarse-textured desert soils, experiments have demonstrated that daily fluctuations of 350 to 400 centimeters of water at a depth of 6 inches are common. The fluctuations diminished with depth and were no longer apparent below 48 inches. Results in other areas have shown that the magnitude of fluctuation is much less on medium- and fine-textured soils, particularly in places where the daily temperature range is not so great. The substitution of plastic for metal tensiometer parts

can practically eliminate the problem of diurnal fluctuation. When that cannot be done, readings should be taken before or within an hour after sunrise. Tension values observed at that time are a reliable indication of soil moisture conditions where appreciable fluctuations occur.

The limitation of the useful range of tensiometers from zero to 850 centimeters of water, or 0.85 atmosphere, is not objectionable in sandy soils, as 80 to 90 percent of the moisture available to plants is held at tensions of less than 1 atmosphere. In comparison, approximately 45 percent of available moisture in fine-textured soils is covered within the same limits of soil moisture tension. In instances where tensiometers tend to go off-scale rapidly, the porous cup can be placed deeper in the soil to allow greater depletion of soil moisture in the surface layers if desired. The depth of installation will depend on the rooting characteristics of the crop and the overall removal of moisture from the root-zone reservoir.

Another procedure consists of installing the porous cups at a uniform depth in the active root zone and delaying irrigation for some time after the upper tension limit of the instrument has been reached. The additional period allowed between irrigations is set arbitrarily at a fraction of the time, one-third or one-half, required to attain this maximum tension limit. Thus, a workable tension limit attained 6 days after irrigation would require that the irrigation interval be extended an additional 2 or 3 days. Such a procedure allows a flexible irrigation interval beyond the tensiometer range dependent on the rate of depletion of soil moisture.

A variability between tensiometer readings in a given plot area is usually associated with nonuniform soil moisture conditions. Poor distribution of water, differential extraction of moisture by plant roots, soil heterogeneity, compaction, et cetera, are factors that contribute to variability of soil moisture. Placement of tensiometers in the same relative position with respect to furrows and water source can reduce the variation.

A tensiometer is the most accurate instrument we have for measuring the tension of soil water. Sensitivity in static or slow-moving systems is equal to or less than 1 millimeter of mercury on a manometer. An instrument with such accuracy is suited to measurements of hydraulic head and hydraulic gradient of soil water near field capacity. A single, compact, multiple-cup tensiometer, designed for the purpose by L. A. Richards, permits simultaneous measurements of moisture tension at intervals of about 4 inches in the upper 2 feet of the soil profile. The use of the tensiometer to measure the tension of soil moisture is quite similar to the use of a voltmeter in relation to electricity—that is, it will always be used as a reference instrument.

Early efforts to measure the electrical resistance of soil in relation to its moisture content were unsuccessful. The method commonly used consisted of two electrodes buried in soil, and the measurements were made with alternating current to avoid polarization. But salt in the soil affected the soil moisture-resistance relationship and the variation in contact resistance between electrodes and soil, due to contraction and expansion of soil around the electrodes, gave erratic readings.

A practical solution to the problem was demonstrated in 1940, when G. J. Bouyoucos and his associates at the Michigan Agricultural Experiment Station introduced a unit that employs a block of plaster of paris. It consists of two electrodes made of straight wire or a 20-mesh screen of stainless steel, cast in plaster of paris, which serves as an absorbent material. When buried in soil, plaster of paris becomes essentially a part of the soil and responds to changes in content of soil moisture. Fluctuations of moisture in the block affect the amount of gypsum in solution, which in turn determines the

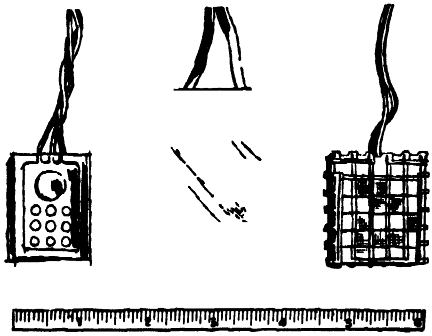
electrical resistance. Thus resistance provides an indirect measure of soil moisture when the block is calibrated for a particular soil.

Other materials, such as nylon, fiberglass, and combinations of them with plaster of paris, have been used as absorbent materials to enclose electrodes. The nylon unit, also developed by Dr. Bouyoucos, consists of two pieces of stainless steel screens, which serve as electrodes. They are separated and wrapped by three single pieces of nylon fabric. Wire leads are silver soldered to each electrode, and the parts are enclosed in a perforated stainless steel case. Pressure is applied to the assembly to provide uniform contact between the electrodes and nylon. The perforated case is clamped at the edges while still under pressure to hold the unit together.

E. A. Coleman and T. M. Hendrix at the California Forest and Range Experiment Station developed the fiberglass unit, which is similar to the nylon unit. The moisture-sensitive element is made from two monel screen electrodes separated by two thicknesses of fiberglass cloth. Three additional wrappings of the same cloth are made around the electrodes. The moisture-sensitive sandwich is enclosed in a monel metal case with perforations in each side. The case is die-formed in identical half-shells to insure dimensional accuracy and rigidness. When assembled and spot welded in place, the case serves to compress the fiberglass uniformly. A thermistor in each unit provides temperature readings when desired.

Nylon and fiberglass units provide greater sensitivity in the higher ranges of soil moisture than plaster of paris blocks. One objection to their design and use in the field arose from imperfect contact with the soil alternately wet and dry. The outside metal enclosure, which minimizes the tendency for electrical measuring currents to pass through the soil outside the unit, apparently prevents intimate contact between the fiber and soil particles. The response of the unit to moisture changes in the soil is often erratic and unreliable under such conditions.

The desirable features of the plaster of paris block and units utilizing nylon or glass fiber as an absorbing medium were combined in a unit described by R. E. Yonker and F. R. Dreibelbis, of the Department of Agriculture. A layer of fiberglass is placed between electrodes and plaster of paris, thus imparting sensitivity in both the wet and dry range of soil moisture and providing good contact between soil and unit. Bouyoucos has modified his methods by casting a complete nylon unit inside a plaster of paris block. An increase in sensitivity within the wet range of soil moisture, without sacrificing accuracy in the dry range, is possible with the unit.



Resistance units for measurement of soil moisture. (Left, fiberglass; center, plaster of paris; right, nylon.)

Electrical-resistance units for measuring soil moisture can also be calibrated in terms of tension or available moisture. Sensitivity of the measurement depends on relative attraction of soil and block material for water at various moisture contents. Nylon units are most sensitive at tensions less than 2 atmospheres, but plaster of paris blocks function most effectively between 1 and 15 atmospheres. Fiberglass units operate satisfactorily over the entire tension range of plant available moisture. None of the resistance units, however, is as sensitive as the tensiometer within the one atmosphere tension range.

A serious objection to use of plaster of paris as an absorbent medium is its lack of durability. If the soil is waterlogged or if frequent applications of water are made on coarse-textured soils, a unit may disintegrate in one season. An improvement in durability of the block was made when Bouyoucos used plaster of paris impregnated with alcohol-soluble nylon resin.

Electrical-resistance methods for measuring soil moisture generally are sensitive to salts in the soil profile. Fiber units are more sensitive than units made of plaster of paris. The latter contain a saturated solution of calcium sulfate when wet. A salt concentration less than the amount in the block has only slight effect on resistance of the unit.

TEMPERATURE also affects the resistance reading of all units, but the magnitude of resistance change is small relative to other sources of variation. Sterling A. Taylor and his associates at the Utah State Agricultural College found that the variation between plaster of paris blocks arises largely from two sources—random variation among blocks and drift from calibration. The coefficient of variability between blocks was about 15 percent. The variation could be minimized by selection of units which did not differ by more than 50 ohms after plunging in water. Calibration drift of some units caused changes of as much as 1 atmosphere tension in a single season. The magnitude of the change depends on the number of drying intervals and the number of days between each drying interval. Changes in calibration were greater in the wet range (low resistance values) than in the drier moisture range. Units treated with nylon resin were more resistant to changes in calibration, becoming considerably more stable after 10 wetting and drying cycles. The nylon and fiberglass units are relatively stable in comparison with either the plaster or resin-impregnated blocks.

After extensive studies of various methods of measuring soil moisture in the field, the investigators concluded that the greatest source of variation was due to real differences in content of soil moisture. Uneven application of water, differential removal of water by a crop, variations in texture, fluctuating infiltration rates caused by cracks, and compaction by tillage implements, sealing of the soil surface by rainfall, and other factors contribute to moisture variability and field sampling error. The possibility of reducing the coefficient of variability below 10 percent with gravimetric procedures appears unlikely for field sampling of moisture in most soils. Therefore any indirect method approaching this precision would have use in the field. Tensiometers and plaster blocks are in this category. Further study on units utilizing a combination of plaster and fabric is needed to ascertain their variability.

The thermal method, although sound in principle, is not available commercially because of difficulties encountered in construction of a suitable thermal unit. In 1939, B. T. Shaw and L. D. Baver, then located at Ohio State University, introduced the idea that heat conductivity of the soil could be used to provide an index of changing moisture conditions in the soil. Numerous attempts have been made since then to devise a unit suitable for making continuous measurements of soil moisture in the field.

Unit design, as developed originally, required that the heating element, consisting of an enamel-coated copper wire coil, be placed in direct contact with the soil. The instrument gave good results in the laboratory. Field installations, however, gave unreliable results because of unit-soil contact difficulties encountered with alternate wetting and drying. Consequently most units have been developed with a heating element embedded in a porous medium.

The wire-basket technique permits drying from all sides of the one-half inch layer of soil surrounding the unit.

Equilibrium between the soil and unit is achieved by placing the apparatus in a humidity chamber for 19 hours following a drying period of 5 hours. The entire system is removed periodically from the humidity chamber and weighed. At the same time the unit resistance is noted. When no further loss in weight occurs, a final moisture determination is made of all soil in the basket, and the moisture percentage based on the weight of the system at the end of each drying period is computed. Loss of weight due to removal of moisture from the block must be included in the overall loss of moisture from the system.

ANOTHER TECHNIQUE consists of embedding units in soils of varying moisture in friction-top paint cans. Wire leads from the unit are brought through a hole in the lid and sealed with cotton and wax. Periodic readings are taken under constant temperature conditions until no further change in resistance of the unit is noted. Moisture determinations made at that time can be correlated with resistance to give a calibration curve. The method is not suited to calibration of a single unit. When a large number of similar blocks are to be used, however, the procedure has merit.

Resistance units can be calibrated to read soil moisture tension with the pressure-plate and pressure-membrane apparatus developed by Dr. Richards and his associates. The resistance-tension relationship is obtained by embedding units in a medium-textured soil low in soluble salts. After the soil and units are placed on the permeable membrane of the extraction cell and saturated with water, a given pressure (or suction) is applied to the system. Outflow of water from the soil and blocks occurs until equilibrium with the applied pressure (or suction) is attained. When resistance of the units has been determined, the pressure applied is increased. This procedure is continued until sufficient points at given suctions are available for a calibration curve. Similar calibrations within the tension range of 0 to 0.85 atmosphere can be made in the laboratory or field with a tensiometer installed near the resistance unit.

Within the limitations that have been discussed, resistance units calibrated in terms of tension provide an indication of moisture available to a crop. As available moisture is related to the force or tenacity with which water is held in the soil, the moisture content need not be determined. Thus a single calibration curve for resistance units theoretically should apply to all soils, regardless of texture. As I pointed out, however, factors such as salt concentration, calibration drift, and variability between units, affect the resistance-tension relationship and must be considered if readings are to be interpreted correctly.

PRACTICAL APPLICATIONS of moisture-measuring devices should be—but are not—of particular interest to all irrigation farmers. There are several reasons for this lack of interest among some farmers: Water is not available on demand in many irrigated projects—a farmer must take his turn for water at designated intervals, and he is obliged to irrigate more or less on a calendar basis. When water is delivered to his farm, he must take the entire stream, which often means irrigating day and night to get the job done. Under such conditions, farmers are not able to use advantageously moisture meters as a scientific guide to irrigation. Irrigations also must be scheduled to fit into other farming operations. Thus a farmer might elect to irrigate a crop sooner than necessary because he anticipates harvest of hay the following week. Finally, some farmers are reluctant to use even a soil probe or shovel to examine moisture conditions before and after irrigation—to say nothing of a seemingly complicated instrument.

In places where water must be pumped from great depths and supplies are limited, the use of moisture

meters is becoming popular as a guide to irrigation and conservation of water.

Several moisture meters with resistance units are available commercially. Those utilizing an electric eye to indicate the null point are difficult to read in daylight, and are not well adapted for field use.

A resistance bridge equipped with headphones was designed by Dr. Bouyoucos to measure resistance in circuits containing considerable capacitance. This instrument is essentially a Wheatstone bridge of considerable accuracy and ruggedness. Resistance measurements in the field can be made rapidly and easily. Little technical training is required. A reading requires only a few seconds and several hundred determinations can be made by a technician in a day. The instrument, however, would not be recommended for general use by farmers.

OPERATION of the thermal unit is based on the principle that heat conductivity of water in the soil is much greater than that of the soil itself. Thus, when a constant current is passed through a heating element for a given period, the amount of heat that is conducted away from the unit depends on the amount of water present in the porous medium or soil. Since heat conductivity is high in moist soil, the element remains cool and has a relatively low resistance. As the soil dries, heat conductivity of the soil water becomes less, and the subsequent rise in temperature of the element causes a corresponding increase in resistance. The relationship between resistance and soil water provides an indirect measurement of soil moisture.

Thermistors, a thermally sensitive resistor, have also been used as a combined heating source and resistor in place of a copper wire coil. Temperature corrections are necessary with the instrument, however, and design problems have not been solved entirely. Thermistors have also been adapted to measure the temperature rise of a heat-sensitive indicator (thermistor) at some predetermined distance from a heating element.

Men working with the Civil Aeronautics Administration in Indianapolis have devoted considerable effort to development of a workable thermal unit of this type. More than 50 moisture cells of various designs have been tested and evaluated. Some of the units had limited applications, but none was entirely satisfactory over the range of moisture contents encountered in both civil engineering and agronomic use. The major unsolved obstacle—a permanent porous material with proper pore-size distribution in which a thermal-sensitive device can be embedded without damage to the element.

The development of a neutron method became possible when radioactive materials were made available. Hydrogen nuclei are effective in reducing energy and high velocity of fast neutrons. Collision and scattering of neutrons traveling away from a radioactive source cause some of the neutrons to return to the source, or immediate vicinity, as slow neutrons. Thus the greater number of hydrogen atoms in the soil, the greater will be the number of slow neutrons present in the system. As most of the hydrogen nuclei occur in water, the number of slow neutrons can be measured and correlated with the amount of water in the soil.

SINCE THE original work of D. J. Belcher and his associates, who cooperated with the Civil Aeronautics Administration, attempts have been made to adapt the neutron method for field measurement of soil moisture. Studies of S. A. Taylor and associates with portable equipment indicate that precision of the method is not so good as that obtained with carefully calibrated resistance units or tensiometers.

Noteworthy advantages of the neutron method include field installation with minimum disturbance to soil and sensitivity over the entire range of available moisture. Field measurements of moisture are usually made in metal access tubes approximately 1

inch in diameter and sealed at the bottom. The tubes are placed in the soil to desired depths in holes made with a 1-inch soil auger. A moisture probe, consisting of the neutron source and detecting chamber, is lowered into the tube when measurements are made. Since neutrons readily penetrate the metal tube, exploration of moisture in the profile can be made by raising or lowering the probe inside the tube. The volume of soil contributing to the return of slow neutrons depends on the moisture content. The scope of influence is less when the soil is moist than when it is dry. As the neutron method provides an indirect measurement of soil moisture, it is necessary to have a calibration curve.

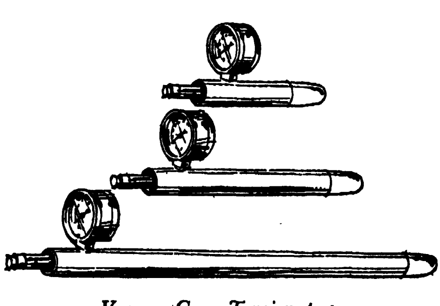
Calibration of moisture units to indicate soil moisture content is necessary for all types of instruments. A disadvantage of most methods of calibration involves artificial packing of fragmented soil samples to simulate field conditions. Resistance-moisture relationships derived from laboratory calibration should always be checked in the field. Field calibration of units should be made where soil moisture is being removed by roots of actively transpiring plants. Under such conditions, units respond rapidly to changes in soil moisture content and are more apt to reflect the true calibration curve of the soil.

Selection of a laboratory method to calibrate moisture units depends somewhat on the individual and facilities available. Some workers feel that reliable calibrations can be made only when units are buried in a soil-filled container permeated with roots of growing plants. Field conditions are more nearly simulated using this procedure, but a considerable amount of time is involved if extended through several drying cycles. Others have resorted to more rapid techniques, whereby units are embedded in soil contained in a shallow metal pan or in a cloth-lined wire basket. With the shallow pan technique, only one-eighth inch of soil surrounding the block is used for the moisture determinations after drying of the soil has progressed to various stages. Resistance values determined when the soil is scraped from the unit are correlated with the moisture content of the soil samples obtained at various drying periods.

A moisture meter designed by Dr. Coleman for use with Fiberglas units consists of a battery-operated, alternating-current ohmmeter. Resistance measurements are made by relating the reading observed on a micrometer to a calibration curve. This instrument provides adequate sensitivity for all resistance units under normal field use. It is simple and does not require headphones.

An instrument designed specifically for use by farmers was also developed by Bouyoucos. It operates on the principle of an ohmmeter and is calibrated to read the approximate percentage of available moisture when used with plaster of paris blocks. When it is connected to the wire leads of a block, movement of a needle across the dial indicates the extent to which soil moisture has been depleted. It is simple to operate, but it is not entirely satisfactory for coarse-textured, peat or muck soils and soils with relatively high salt content.

Tensiometers equipped with vacuum gages are being used successfully by commercial growers. Some skill is required to use them. Construction problems inherent in original designs have been minimized by utilizing plastic



Vacuum Gage Tensiometers.

materials. With reasonable care, they should give good service for a number of years. They are particularly adapted to use in medium- and coarse-textured soils.

An adequate field installation for irrigation control costs from 150 to 300 dollars, depending on the type of meter and number of resistance units used. Moisture meters cost 65 to 200 dollars. Resistance units cost 1.30 to 3.50 dollars each. Plaster of paris blocks are the least expensive and most practical of the resistance units available commercially. Tensiometers, costing about 25 dollars each, are a self-contained moisture meter, which needs no additional apparatus to indicate field moisture conditions. It takes only a glance to read the needle on the vacuum gage.

Automatic irrigation of lawns, golf courses, and high-value crops grown under permanent sprinkler systems in the field or in the greenhouse is now possible with equipment developed for the purpose. Two types of installations are available commercially. One involves the use of a nylon resistance unit in connection with a solenoid valve and electric controller. The other has a hydrostat and a remote control valve operated hydraulically. The instrument utilizing the nylon unit was developed by Bouyoucos for use in greenhouses but could be adapted for other field uses. The method requires that a continuous current of electricity be maintained between the electrodes of the resistance unit. As the soil becomes dry and the resistance of the unit increases, a point is reached when the electrical controller actuates the solenoid valve installed in the water line of the overhead irrigation system. When enough water has penetrated the soil to the depth of the unit. the resistance is lowered and the water automatically turns off.

An automatic irrigation control utilizing a hydrostat and remotely controlled hydraulic valve was invented by Dr. Richards. It was designed specifically for irrigation of lawns equipped with underground sprinkler systems. The automatic controls are operated hydraulically and no electrical source of energy is needed. The hydrostat is equipped with a porous cup, which functions as a tensiometer. When the tension or suction of the soil water approaches a predetermined limit, a vacuum is created, which opens a valve in the hydrostat and permits water to flow through a small copper tube connected to the remote hydraulic valve in the sprinkler line. The reduction in water pressure opens the remote hydraulic valve and permits water to flow in the irrigation system. The sprinklers will continue to operate until stopped by a built-in timing mechanism, which closes the remote valve at a predetermined time. The hydrostat can be operated manually if desired.

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The national interest demands that the application of soil and water conservation be speeded up on the farms and ranches and on the watershed, grazing, and forest land throughout the United States.

—Ezra Taft Benson

And he gave it for his opinion, that whoever could make two ears of corn, or two blades of grass, to grow upon a spot of ground where only one grew before, would deserve better of mankind, and do more essential service to his country, than the whole race of politicians put together.

—Swift

When To Irrigate and How Much Water To Apply

Sterling A. Taylor and C. S. Slater

Plant roots will not grow in dry soil. Water from rain or irrigation that fails to moisten the full depth of dry soil will encourage shallow rooting, which often is undesirable. If only the upper part of the dry soil is wetted, losses by evaporation are increased and plant growth is retarded more quickly than if the entire root zone is moistened.

Too little water to moisten the root zone and too much water both produce undesirable effects on crops and waste water that may be needed for other purposes or in other places. It is therefore highly desirable to apply enough water to moisten the root zone without excessive loss by deep percolation, except when you have to leach the soil of undesirable salts.

Water moving into dry soil forms a distinct wetting front. Dry soil is slower to wet than moist soil and the wetting front is sharper in the drier soils. Consequently, when a limited amount of water is applied to dry soil, the water will be distributed unevenly. The surface soil becomes moist, but the subsoil remains dry.

Water will continue to move from the moist soil to the dry soil for a long time, but most of the movement will be completed after a day or two. The amount of water retained after 1 or 2 days of drainage, expressed as a percentage of the dry soil by weight or volume, is known as the field capacity of the soil. It is not an exact figure, because the movement may not cease. The degree of dryness before application of water and structure or texture also cause changes in the amount of water the soil retains.

Work is required to remove water retained by the soil. Curves that relate the amounts of water retained by a soil at different moisture contents and the work required at each level to remove a unit of water are called moisture-release curves. More work is required as the soil becomes drier. Because a given force acting over a given distance produces work, the force or pressure per unit area is used as a measure of the retention of water by soil. This force of retention is called moisture tension.

When measured in the field, water is retained at about 1.5 pounds per square inch, or one-tenth atmosphere of tension, when the soil is at field capacity. When disturbed samples are measured in the laboratory, the same moisture content is obtained at about 5 pounds per square inch, or one-third atmosphere. The difference is probably a result of changing outflow boundaries; the flow of water from disturbed soil to a membrane or ceramic plate is vastly different from the flow in undisturbed soil.

Although the plant roots take water freely from soils at field capacity, the work required to remove the water becomes progressively greater as the soil becomes drier and the forces of retention increase. Different soils release different amounts of water for each increment of work. Whenever the soil moisture is reduced to a point that a large change in work is required to remove only small amounts of water, the plant will soon suffer from moisture deficiency. Water should be applied before that point is reached by most of the soil in the root zone or plant growth is checked.

Soils in which the moisture content is depleted until plants wilt and fail to recover when placed in a moist atmosphere in the dark are said to be at the permanent wilting point. This represents the lower limit of available moisture. Like field capacity, the wilting point cannot be determined exactly, and it cannot be found for some soils, particularly salted soils. For many soils the permanent wilting point lies within the range of moisture tension from 10 to 20 atmospheres. The

percentage moisture at 15 atmospheres is considered frequently to be equivalent to the permanent wilting point. Approximately 45 times as much work is required to remove moisture at the wilting point as is needed at field capacity. Although all the water from field capacity to permanent wilting point is considered to be available to plants, they wilt temporarily long before that point is reached.

The soil may be considered roughly as a reservoir for soil moisture, with the upper limit at a moisture content corresponding to field capacity, and the lower limit at the permanent wilting percentage. Roots correspond to a pump with many inlets that may penetrate deeper into the reservoir as the crop grows. As the soil gets drier, more energy is required to pump the water out, for it is getting lower in the reservoir. A distinct and important difference exists at this point between a true reservoir and the soil. The water in a reservoir is free to run to the pump inlet and moves more rapidly than the pump can extract it. Water in the soil is not free to move to the plant roots, and it may move much more slowly than the roots and plant can remove it. Then the plants may wilt, only to recover when the demand is reduced.

Coarse soils transmit water faster than fine soils when the water is retained at low tensions. At higher tensions, however, water movement is more rapid in fine soils.

FREQUENCY of irrigation and amount of water to be applied are affected by the fertility of soils. Unless enough nutrients are available to the plant to produce maximum growth at all times, nothing will be gained by keeping moisture available at low tensions. Nitrogen may accumulate in the soil during periods of slow growth when moisture tension is high; then, when water is supplied, the crop may use up the accumulated nitrogen rapidly. If moisture is kept constantly at low tensions, so that it never limits growth, the nitrogen may still become available at about the same rate and crop yield may be about the same. The plants might show nitrogen-deficiency symptoms in one instance but not in the other. The most desirable frequency of irrigation can have maximum benefit to the crop only if a supply of readily available nitrogen is present in the soil.

SOMETIMES MATURITY of a crop is delayed by periods of low moisture during its vegetative stage. If sweet corn is kept moist and is fertilized with large amounts of nitrogen and has enough of the other nutrients, it will mature as much as 2 weeks earlier than corn with limited fertilization that also is constantly moist. If moisture tension increases just a little during the early, fast vegetative stage of growth, the early maturity is lost and yields are lowered.

Phosphorus is taken up by plants more easily from moist than from dry soils. Because phosphorus does not move appreciably in the soil, it is taken up from the same relative depth at which it is applied. A common practice is to apply fertilizer near the surface. If so, and if phosphorus is the limiting element, light, frequent irrigations may produce growth far out of proportion to their value in ideal conditions.

CROPS RESPOND differently to moisture tension at different stages of growth. When vegetative growth is rapid, plants react quickly to moisture stress. If the soil becomes dry at this time, new leaves do not develop fully, and a general reduction in succulence follows. When water again becomes available, rapid growth may be resumed, but the small leaves and stems produced under high moisture stress never become fully enlarged, and the plant seldom catches up with the plants that were not subjected to the stress. Potatoes are sensitive to soil moisture from planting until the tubers are fully formed. Sugar beets are most sensitive in the seedling stage and (like most other crops) continue sensitive until

the growth rate is retarded by maturity. Field corn requires water at low tensions from seeding to hard-dough stage for maximum growth and yield. It is particularly sensitive to moisture stress at silking time and shortly thereafter. Small grains are similar to corn. Very little difference in yield can be demonstrated by moisture variations during the ripening period.

Tobacco transplants are resistant to moisture stress for relatively long periods of moisture deficiency, but when enough water is once supplied to initiate rapid vegetative growth, a continuance of water at low tension is required to develop the crop properly.

Peaches are particularly sensitive during the period of rapid enlargement of the fruit. Apples enlarge at an almost uniform rate and need a steady supply of readily available moisture.

Maintenance of low moisture stress assures a maximum of vegetative growth but does not always assure the quality and quantity of the marketable crop when fruits and seeds are harvested. The quality of apples and pears may be improved by restricting the supply of irrigation water during the ripening period. Water is then required again near picking time to prevent desiccation and injury to next season's fruit buds during the winter.

Truck crops need to be grown at high moisture levels to develop the succulence and tenderness that the market demands. These crops respond well to light, frequent irrigations because they are relatively shallow-rooted. Deep-rooted crops, such as alfalfa and orchards, may produce well with heavy, infrequent irrigations, and many annual crops, such as corn, cereal grains, and sugar beets, are intermediate.

YOUNG PLANTS that only partly cover the ground have very small root systems. Such plants need water just as much as when they are older. They should not be allowed to suffer for water in the mistaken belief that the root system thereby will be forced downward into deep soil. Plant roots grow deeper in soils that are kept moist, but not wet, during the early stage of growth. It is true that the root system is capable of rapid growth at this stage, but the growth of both roots and shoots is reduced during any period when moisture is deficient in that portion of the soil already occupied by roots and the plant that so suffers generally is permanently retarded by the adverse condition. Sometimes the retarded plants may be allowed to grow for a longer period than the other plants and produce an equal yield, but usually that is not the case.

Water should be applied for a long enough period to get sufficient water in the soil to moisten the dry soil without appreciable amounts moving into the moist soil below. In order to bring this about, water must be turned off shortly before the entire root zone becomes wet. Subsequent drainage for the next 24 hours will be sufficient to moisten the balance of the soil in the root zone and deep percolation will not be excessive.

The application of water should be slow enough to avoid erosion and water wastage through runoff. Many soils take water at rates between one-fourth inch and 1 inch per hour. High infiltration rates are favorable to the use of sprinkler irrigation systems. In furrow irrigation, high infiltration causes more water to enter the soil near the head of the field before the area is covered and, in extreme cases, results in excessive penetration there while irrigation at the lower end is still deficient.

THE TIMES when irrigation water should be applied can be determined despite the many variables. To do it most accurately you must know the depth of soil from which moisture is being extracted and the moisture tensions throughout that depth.

You can determine the depth from which water is being extracted by using one of the several methods of measuring soil moisture, as described in pages 362–371.

If determinations are made at several depths and at regular intervals, the varying rates at which moisture is being removed from different depths can be observed. If no active plant roots are present, the rate of moisture removal is slow. Moisture tensions may be determined at the same time as the depth of rooting. The instruments indicate tension directly or are otherwise calibrated to register tension or moisture content which can be converted to tension by using moisture-release curves.

Available water will still be present in the root zone in appreciable quantities when the time to irrigate arrives, because of the way water is removed by crops. Plants draw a disproportionate amount from the upper soil where their concentration of roots is greatest; evaporation also removes water most readily from the surface soil; thus when 60 percent of the available water has been removed from the upper quarter of the root zone, exhaustion of the entire root zone may be less than 30 percent. Relative amounts will vary with crops, weather and soil conditions, but the wilting point is reached first in the upper soil. Irrigation is needed when only a part of the root system is restricted in supplying water to stems and leaves.

Best results with irrigation are obtained for most crops if water is applied before the average tension in the zone of rapid moisture removal goes above 4 atmospheres and if irrigation is withheld whenever the tension is below one-half of 1 atmosphere. Tension-indicating meters or resistance units for measuring soil moisture may be placed at various depths and read periodically to indicate these moisture conditions that represent a range of about 30 percent to 80 percent of the total water retained between field capacity and the permanent wilting percentage on many soils.

A commonly accepted generalization calls for irrigation when 60 percent of the available water in the root zone is depleted. If water additions are confined solely to irrigation, fields may be irrigated in sequence as they approach that level. Rainfall at any time before or during the growing season, however, may result in approximately the same moisture level over the entire area. Irrigation may be needed later.

If the farmer has a large number of fields and irrigates one or more of them a day, the moisture level in the last tract may be at or near the wilting point by the time he gets to it. He should start soon enough to arrive at the last field before its available water is completely exhausted. This is the reason for irrigating in a range of from 30 percent to 80 percent depletion. If this range represents 3 inches of available water in the root zone and consumptive use is 0.3 inches a day, he has about 10 days to complete his irrigation. Soil moisture will seldom be reduced to the permanent wilting point before irrigation is applied if some good method is used to indicate in advance the water status of the soil.

Very sandy soil may have a capacity of less than 1 inch of available water per foot depth of soil. Clays and organic soils may retain 2.5 inches or more. The range for most soils lies between 1 and 2 inches for each foot of depth. To express these figures as volume percentages, the depth of water retained is divided by the corresponding depth of soil (in inches) and multiplied by 100.

The amount of water to apply to replenish the moisture in any depth interval of soil can be calculated by subtracting the amount of available water that is present from that which the soil will hold without deep percolation loss. If this value is stated as a volume percentage decimal, it need only be multiplied by the depth of soil in the sampling interval to convert it to a depth of water per acre. If the depth interval is 6 inches and the volume percentage is 20, then the amount needed to restore that 6-inch interval is 1.2 inches. Any additional water will

penetrate to the next lower 6-inch interval. If that interval requires a volume percentage of 15 percent to restore its moisture, the amount of water it will hold is 0.90 inch. Each interval can be calculated and the amounts added to give the amount needed to restore the moisture in the entire root zone.

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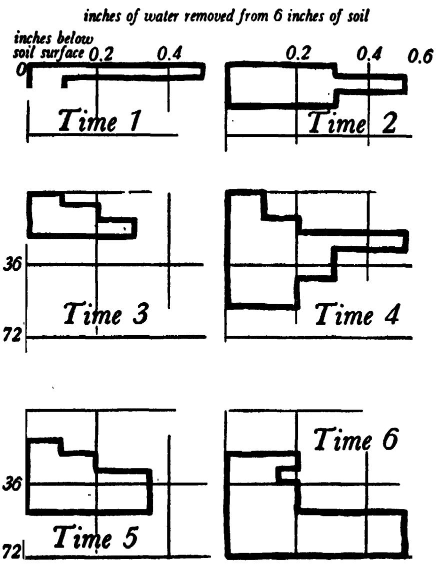

Water removal patterns for Millville loam for successive time intervals after a thorough irrigation. Water is first removed from the surface soil; as the moisture is reduced, it becomes harder to get and removal comes from successively lower depths. The total water removed in any time interval depends on weather and stage of growth of the plant.

Irrigation of Tobacco, Peanuts, and Soybeans

D. M. Whitt and C. H. M. van Bavel

Tobacco is not unusually sensitive to drought. Even in the driest years reasonable yields, although often of inferior quality, are obtained. Nevertheless, the irrigated acreage in several States doubled in 1953.

The reason for the great interest in irrigating tobacco is its high acre value, which is greater than that of any other major field crop. An increase in yield or quality of only 5 percent is valued at 30 to 60 dollars an acre.

The moisture requirements of tobacco are not much different from those of other crops.

The main factor is the time of the year. Places where tobacco can be planted early, such as Florida and South Carolina, therefore, have a natural advantage, because losses from evaporation during April and May are much less than in June and July, and drought is less likely to occur.

We lack accurate data on the amount of moisture lost by evaporation and transpiration from tobacco fields. Depending on locality, they probably run around 0.10 inch a day in April; 0.14 in May; 0.18 in June; 0.17 in July; 0.14 in August; and 0.11 inch a day in September. The rates for quite small plants are lower. The peak rates can be much higher than the average—up to 0.25 inch a day in June and July. At times higher values are quoted by investigators, but the high values may be in error because of deep seepage or lateral evaporation that were not accounted for. It is not known what effect the gradual ripening and the harvesting of the leaves has on the water losses from tobacco.

Tobacco is shallow rooted. The depth from which tobacco extracts moisture is estimated to be 8 to 18 inches.

The climate of the eastern United States commonly is not such that suitable conditions of soil moisture can be maintained always in a relatively shallow root zone. As an average value and by way of example, one may assume a storage capacity of 1.5 inches for tobacco soils. The number of days in which moisture is below the critical level in North Carolina, then, was found to be about 33 in an average growing season. More than one-half of the 33 days occur in June and July, when tobacco grows most rapidly. The situation is even less favorable in one-half of the seasons.

Similar calculations have not been made for the whole eastern area, but it is evident that in most States summer drought is a regular occurrence when root zones are shallow.

Responses of tobacco to irrigation are consistent but never spectacular, because tobacco can recover from dry conditions. A fairly normal crop may result despite early drought when the plants are small. When the crop is full grown, a certain amount of recovery also takes place when a drought is followed by rain. But in that event, quality often is adversely affected. Experiments in Florida, Georgia, North Carolina, Virginia, Maryland, and Connecticut showed increases in yield from less than 100 pounds up to 400 and 500 pounds an acre, or 5 to 25 percent.

The increases reflect the seasonal rainfall and the system of irrigation. In general, there has been no evidence of any beneficial effects or savings by withholding water from tobacco temporarily. Research in Australia and North Carolina tends to show that it is best to keep the soil at optimum moisture level throughout the season. The belief that early irrigation would result in shallow root systems is without scientific foundation. If the supply of water limits irrigation to only a couple of applications, however, it seems generally agreed that the irrigations should take place when the tobacco is about knee-high.

The effect of irrigation on quality and chemical composition of tobacco is considerable. Tobacco is graded, and the grade determines the price. Growers and researchers have known always that tobacco produced in wet years tended to be of superior quality to that produced in dry years. With aid of irrigation experiments, that relationship could be studied further.

Several experiments have revealed that the price of flue-cured tobacco could be increased 10 to 25 percent as the result of irrigation. We have reports of similar effects on cigar tobacco and wrapper leaf. The improvements in quality are related to changes in chemical composition. Irrigation often results in a drastic reduction of nitrogen and nicotine content and in increases in the sugar content of the leaves.

Sprinklers are used almost entirely in irrigating tobacco. Because tobacco usually is planted in wide rows—from 3.5 to 4 feet wide—and the root system is not very extensive, furrow irrigation would give inefficient use of available water supplies.

In view of the danger of "drowning" tobacco by rains that unexpectedly follow irrigation, growers often prefer to use fairly small applications of water at one time—between 1 and 2 inches. The operating costs of an irrigation system are increased by using frequent, light irrigations. When the soil conditions do not permit rapid drainage and on sloping land, rows should be laid out with proper fall, so that surface drainage is adequate. That would be true regardless of the use of irrigation.

Chloride (chlorine) in excessive amounts lowers tobacco quality. Therefore the use of saline or brackish water for irrigating tobacco is objectionable. Occasionally that problem arises along the Atlantic coast when surface water is used. Farther inland, water from wells may contain excessive amounts of chloride. No exact data on the maximum chloride content of irrigation water when used for tobacco are available. But it looks as if water containing

more than 25 parts per million of chloride should certainly not be used.

Such irrigation water would deposit 6 pounds of chloride an acre for each inch of irrigation water. Present fertilizer recommendations call for less than 30 pounds of chloride per acre to be applied to tobacco as fertilizer. Therefore, in case of doubt, irrigation water should be analyzed for chloride.

The nitrogen balance is an important aspect of raising good tobacco. That is, enough nitrogen should be available in the soil to obtain a good yield, but not in an amount that causes the nitrogen content of the leaves to be too high. The problem is acute with flue-cured tobacco; it occurs also with other types. Conditions of soil moisture are important for the nitrogen balance. At present, fertilizer recommendations are a compromise between wet and dry conditions. Therefore, during dry years tobacco quality is not good and in wet years maximum growth is not obtained. Irrigation helps in solving this problem. When a grower can maintain suitable soil moisture conditions, his fertilizing practices are on a sounder basis.

Irrigation helps solve other problems of tobacco production. One is the problem of getting a good stand of transplants. Irrigation permits the grower to set out the plants when they have reached exactly the desirable size. Irrigation immediately after transplanting gives a much better stand and may eliminate the tedious job of watering each plant by hand. Tests have shown that a 0.5-inch application the night after transplanting often gives a 98 or 99 percent stand, compared to an average of about 90 percent. Imperfect stands always result in loss of yield, despite replanting.

Irrigation permits the uniform ripening of the leaves—an advantage that distributes the work load during harvest and allows the efficient use of curing or drying facilities.

Irrigated Acreage of Tobacco (Estimated for 1954)

	Acres	*Percentage of total*
Massachusetts	1,000	17.0
Connecticut	3,000	25.0
Virginia	755	.5
Tennessee	1,000	1.0
Kentucky	6,500	2.0
Georgia	1,500	1.5
Florida	2,500	1.2
Indiana	100	.1
Wisconsin	35	0
South Carolina	1,500	1.2
North Carolina	10,000	1.4
Total	27,890	......

PEANUTS, after cotton and tobacco the most important cash crop in the South, are grown extensively in Georgia, Texas, Alabama, North Carolina, Oklahoma, and Virginia. The most favorable climatic conditions for them are moderate rainfall during the growing season, an abundance of sunshine, and relatively high temperatures. Largest yields are obtained on well-drained, light, sandy loams.

Oklahoma and New Mexico have extensive acreages of irrigated peanuts. The area under irrigation in Oklahoma has been expanding rapidly. The production is centered in Caddo County; 300 farms added irrigation in 1954. Nearly all peanuts produced in New Mexico are irrigated.

Water is applied in the furrow in New Mexico and primarily by sprinkler in Oklahoma. The small acreage irrigated in the Southeastern States is all irrigated by sprinklers. Farmers purchased the equipment primarily for tobacco, cotton, pastures, or other crops and use it on peanuts if water and time permit.

Ralph S. Matlock, after experiments at the Oklahoma Agricultural Experiment Station, estimated that 25 inches of water is required in the growing season for best growth and yield of peanuts. W. J. Vinzant, in trials in Roosevelt County, New Mexico, arrived at the same value. The water requirement reaches a maximum during flowering and pod development. That is the period when most dry matter is being accumulated, and adequate water is needed for maximum yield.

A good practice in New Mexico is to irrigate before planting if necessary to insure ample moisture for germination. Stem root rot is a problem there and planting is usually made on a high, listed ridge. Irrigation before plants show signs of wilting has been recommended. A good rule is to keep the available moisture above 50 percent in the root zone.

Growers in Oklahoma have found the 5-day weather forecast useful in preventing too much irrigation.

Irrigation means the difference between a crop and no crop in New Mexico and southwestern Oklahoma. Three growers in Virginia averaged a 73-percent increase in 1953. Increases in yield ranged from 944 pounds to 1,365 pounds of nuts an acre. Average production without irrigation was 1,529 pounds, as against 2,642 pounds an acre with supplemental water.

The number of Virginia farmers irrigating increased to seven in 1954. W. L. Blair, Jr., work unit conservationist of the Sussex County Soil District, who worked with them, reported an average increase in yield of 59 percent.

Roots of peanuts grow 2 to 4 feet deep—a depth of 6 feet has been reported in the light, sandy soils of Georgia. This extensive root system and its capacity to absorb water may partly account for the lack of widespread irrigation of peanuts in the Southeastern States and much of Oklahoma.

Irrigated Acreage of Peanuts (Estimated for 1954)

	Acres	*Percentage of total*
Oklahoma	10, 000	7. 2
New Mexico	5, 600	100. 0
Virginia	200	. 2
Total	15, 800	....

Soybeans are produced in the United States mostly in the humid East and the subhumid lands of the Great Plains. Illinois, Iowa, Indiana, Minnesota, Ohio, and Missouri have led in production.

The acreage devoted to soybeans in the Great Plains has been steadily increasing. Much of the increase has occurred in localities where irrigation is required almost every year for maximum production.

Approximately 73,000 acres of soybeans were under irrigation in 1954. Arkansas and Nebraska accounted for 68,000 acres of the total.

Climatic requirements for soybeans are about the same as for corn. Drought affects soybeans less than corn. The difference in the effect of dry weather is associated with pollination. The length of the flowering period is longer for soybeans than for corn. A shortage of water during tasselling and silking of corn may ruin the crop. Drought conditions must continue over a longer period to have the same adverse effect on soybeans.

Germination is a critical stage for soybeans. Excess moisture or prolonged drought then adversely affects germination and frequently results in poor stands. When they are well along, soybeans can withstand short periods of dry weather. Experiments at the Arkansas Agricultural Experiment Station showed that soybeans entered an inactive period during dry weather. If the dry period was short, the soybeans resumed development, damage was slight, and the yields were not affected.

The root system of soybeans, not so extensive or deep as that of corn, is quite limited before blooming. The most rapid increase in tops and roots occurs in the 3 or 4 weeks after blooming starts. The use of water corresponds with this growth. It is relatively low from planting to blooming and is greatest for the 2 months following the start of blooming.

Several technicians recommend irrigating when the available soil moisture remaining in the root zone reaches 50 percent. Increases in yield obtained on that basis suggest that it is satisfactory until more definite information is available.

The seasonal water requirement

for soybeans ranges from 13 to 23 inches. Leonard J. Erie and Niel A. Dimick, in experiments at the South Dakota Agricultural Experiment Station, measured average daily consumptive use of 0.14 inch for soybeans from planting to harvesting—approximately the same as for corn, potatoes, and sugar beets. Workers at the Alabama Agricultural Experiment Station indicate an average daily water requirement of 0.18 inch for soybeans for the growing season.

D. M. Whitt, in experiments at the Midwest Claypan Experiment Farm in central Missouri, measured an average daily use of 0.18 inch in June, 0.32 inch in July, and 0.28 inch in August. Those values were determined under irrigation in 1954, a dry year, on small plots and may be high because of lateral evaporation, which was not measured.

The amounts of water that soils can hold for the use of plants range from 0.5 inch per foot of depth in sand to 2.5 inches in clay. The need of the plant for water under equal fertility in a given locality is essentially the same regardless of the soil. Thus soybeans grown on sandy soils will need irrigation or rainfall more frequently than those produced in heavier soils. It is necessary, therefore, to consider the need of the plant for water and the capacity of the soil to supply water in establishing an irrigation schedule.

Sprinkler and furrow irrigation are used on soybeans. Furrow irrigation is used almost exclusively in the Great Plains, where surface methods have been practiced for years. Both methods are used in the humid States. Sprinklers are especially desirable on sandy soils with high water intake rates and on land of uneven topography.

Yield increases from irrigating soybeans vary. E. E. Hartwig, P. Grissom, and W. A. Raney, in studies at the Mississippi Delta Branch Agricultural Experiment Station, measured increases of 5 to 7 bushels above the 24.5 bushels an acre on check plots on a sandy loam soil in 1952. They measured a 10-bushel increase above the 29 bushels an acre on check plots that same year on clay soil. Irrigation increased the size of seeds and delayed maturity. Research workers in Arkansas measured yield increases resulting from irrigation of 2.7 bushels an acre without fertilizer and 3.3 bushels with fertilizer in 9 years, from 1931 to 1939. The increases were 23 and 25 percent, respectively, and the period included 2 years when rainfall in July and August was substantial, and yields on irrigated and unirrigated plots were approximately equal. Yield was increased 5 bushels an acre, from 29 to 34, by irrigation on unfertilized plots the following year.

Soybeans did not respond to irrigation on claypan soil in central Missouri in 1949 and 1950, when yields of corn increased more than 20 percent because of irrigation. An increase from 17 bushels to 31 bushels an acre was measured there in 1953 from a single irrigation of 4.70 inches in August. Rainfall in July and August totaled only 4.10 inches, and lack of soil moisture became critical during the period of pod filling.

The quality of the beans and the oil extracted from them also were affected by moisture in Missouri. It took 4,500 beans from the unirrigated plots to weigh 1 pound, compared to 3,000 beans from the irrigated plots. Oil content was 20.3 percent without irrigation and 22.5 percent with irrigation. The amount of acetone insolubles, a rough measure of the loss in refining the oil, was more than 3 times as great in the unirrigated beans.

Varieties have given different response to irrigation in Arkansas and Missouri. High temperatures usually associated with drought seem to account mostly for the differences. Late maturing varieties generally have been more adversely affected than those which mature earlier. An exception to this occurred in 1954 in the Mississippi Delta studies in southeastern Missouri. Ogden, a full season variety, yielded 9 bushels an acre without irrigation

and 32 bushels with 12.75 inches of irrigation. Dorman, which matured 3 weeks earlier, produced 7 bushels without irrigation and 23 bushels with 12.75 inches of irrigation.

Irrigated Acreage of Soybeans (Estimated for 1954)

	Acres	*Percentage of total*
Arkansas	38,000	4.5
Missouri	1,000	0
Nebraska	30,000	15.8
South Dakota	200	.1
Oklahoma	200	.4
Illinois	500	0
Alabama	20	0
Louisiana	1,000	1.7
Mississippi	2,000	.4
Total	72,920	....

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Irrigating Cotton To Insure Higher Yields

Bert A. Krantz, Norris P. Swanson, Karl R. Stockinger, and John R. Carreker

An increasing amount of cotton is grown under irrigation.

In the West the irrigated acreage in cotton was about 8,600 in 1909 and 2,443,000 in 1949, when 9.2 percent of the total cotton acreage and 18.5 percent of the production was on irrigated lands. The rapid upward trend continued after 1949.

Cotton is grown under irrigation in Arizona, California, New Mexico, Texas, and Oklahoma.

The use of supplemental irrigation in the more humid cotton area, a newer development, was accelerated by the droughts of 1952–1954, better control of the boll weevil, and improvements in fertilization practices. The greatest expansion has been in the more westerly states of the South, notably along the deltas of the Mississippi and Arkansas rivers.

James L. Gattis, of the Arkansas Agricultural Extension Service, estimated that supplemental irrigation was used on 70,000 acres in 1953 and 145,000 acres in 1954 in Arkansas; in 1949 only about 5,000 acres were under irrigation.

P. H. Grissom, of the Mississippi Agricultural Experiment Station, estimated that 43,000 acres were under supplemental irrigation in Mississippi in 1954, and 150,000 to 200,000 acres in 1955. In the rest of the Cotton Belt, interest in supplemental irrigation has been growing, and almost every State agricultural experiment station listed 500 acres or more with supplemental irrigation.

SEVERAL METHODS of irrigating cotton are in common use—furrow, sprinkler, border, and level border, or basin, irrigation. Before he chooses a

method, the cotton farmer should consider the soil permeability, topography, the water supply, costs, and the amount of water to be applied during the season.

The development of lightweight, quick-coupling, portable pipe has increased the use of sprinkler systems, which have several advantages: Little or no land preparation may be required. Terraces and other practices to control erosion and conserve moisture need not be altered. Light and uniform water application can be made as desired. Effective use can be made of small streams of water. The system can be moved to other fields. Disadvantages are increased power costs for delivering water and a comparatively high investment per acre.

Furrow irrigation is most common for cotton, particularly in the Southwest. It is well adapted to deep soils that are nearly level or have uniform and moderate slopes. Farmers living in high intensity rainfall areas should seriously consider the problem of soil erosion before choosing this method. Furrow slopes in such areas should not exceed 0.25 percent (3-inch fall in 100 feet) to be nonerosive. If soils and topography permit their use, level or contour furrows will provide more uniform distribution of irrigation water, prevent erosion, eliminate unnecessary runoff from precipitation, require less labor, and lead to greater yields. Furrow irrigation systems can be planned to utilize a wide range of streams. A very small stream may be used as single furrow stream; a large stream may be distributed to more than 100 furrows.

Furrow-irrigated cotton is normally planted with row spacings varying from 36 to 42 inches, with a furrow between each row. Some farmers use beds with a furrow between each pair of rows on slowly permeable soils. The furrow spacing should fit the standard farm equipment used but should not be so wide that water will not spread to the center of the ridge before it moves down below the root zone.

Successful furrow irrigation requires maintenance throughout the irrigation season of a furrow with a cross section adequate to convey the desired stream of water. In fields where cotton is planted on the bed, that is not a serious problem. Flat-planted cotton, or lister-planted cotton, with the cotton planted in the lister furrows, will require cultivation to provide irrigation furrows between the rows. It may be necessary to irrigate lister-planted cotton in the drill furrow if the plants are not large enough to allow cultivation to build a furrow between the rows by the time of the first irrigation after planting. That encourages early growth of weeds in the row, where they are hard to eliminate.

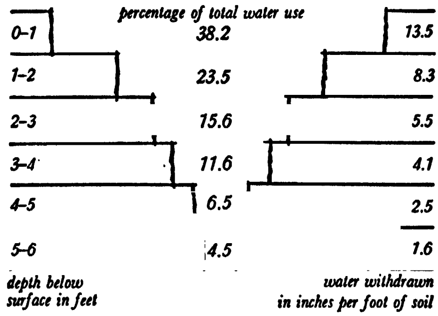
Border irrigation may be satisfactory on fields with little or no side slope. Small streams are not satisfactory for use with border irrigation systems. But large streams, or heads, of water can be utilized with a small amount of labor by irrigating several border strips at once.

Level border, or basin, irrigation provides an excellent degree of control of irrigation water with a minimum of labor. If the conservation of rainfall and prevention of erosion are problems, level or bench borders are used for cotton; the water often is applied to the border strip in furrows. Borders provide for the irrigation of flat-planted cotton and are an effective means of applying leaching irrigations to prevent accumulations of salt in the surface soil.

THE WATER REQUIREMENT of cotton depends on the variety of cotton, the length of growing season, temperature, hours of sunshine, amount and distribution of rainfall, the depth and texture of the soil, and—if leaching of salts must be accomplished with all or most of the irrigations—the quality of the water. An efficient irrigation system will keep losses by deep percolation, runoff, and ditches at a minimum. Irrigation efficiencies of 70 to 75 percent are considered good.

In the humid regions the require-

Water Use From the Soil by Cotton in the Hotter Areas



ments of irrigation water depend on the duration and frequency of summer droughts. John R. Carreker, in experiments in Georgia, increased yields 58 percent with irrigation in the 5 years from 1949 to 1953. He averaged nearly 4 irrigations a year with an annual total of about 7 acre-inches of water. Similar results have been obtained in Arkansas, Mississippi, Alabama, Missouri, and Texas.

From experiments conducted in the San Joaquin Valley of California in 1926 to 1935, the conclusion was drawn that about 24 inches of water is enough for normal production of cotton on a clay or clay loam soil and about 30 inches on the sandy loam soils. Both surface evaporation and plant transpiration were taken into account. It was estimated that total irrigation applications of 15 to 20 inches on the heavy soils, with a maximum 14-inch preplanting irrigation, or 15 to 20 inches on the medium and lighter soils, with an 11-inch preplanting irrigation, would be ample to supply the required 24 inches to the plants in the field.

K. Harris, who conducted experiments near Mesa, Ariz., reported an average annual water use of 36.4 inches of water by cotton. The peak use occurred in August, when the average was 8.3 inches. Nearly as much water was used in July. Similarly, an average annual water use of 35.1 inches was computed from experiments conducted at Shafter, Calif., where 8.9 inches of water was used in August.

P. E. Ross recommends the use of 20 to 25 inches of supplemental irrigation water for cotton in the lower Rio Grande Valley, with up to 5 irrigations if there is no effective rainfall. An average of 15 inches of rain can be expected during the growing season and 24 inches of rain during the average year in the area.

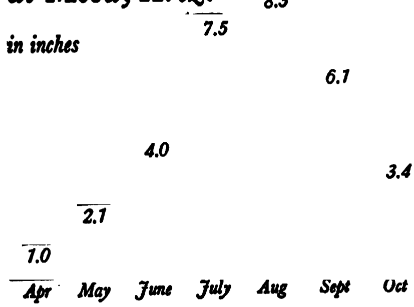
Norris P. Swanson and E. L. Thaxton found that 20 inches of irrigation water was ample for cotton on the clay loam soils of the High Plains of Texas in years of very low rainfall. Water was applied in a preplanting irrigation and three later applications. No irrigation was done after August 15.

D. L. Jones has shown that 6 to 9 inches of supplemental irrigation is satisfactory on the medium-textured soils of the High Plains in years of nearly average rainfall. An average of 15 inches of rain is received there between April and September. Peak daily water use, including evaporation from the soil surface, reached 0.40 inch a day during the hot, dry weather in early August.

An average peak water use of 0.25 inch a day is about normal in most of the cotton-producing areas, however.

COTTON PLANTS develop deep root systems if conditions are favorable. Six factors that affect the root development are: Moisture supply; oxygen

Monthly Water Use by Cotton at Mesa, Ariz.



supply, or aeration; soil temperatures; available plant food; tillage pan; and toxic materials, such as salt or soil-borne plant diseases.

A deep soil and favorable conditions usually enable cotton to root into or through the 6-foot depth of soil by the end of the growing season. Deep rooting is important for irrigated cotton because it provides a greater potential storage of soil moisture. If the root zone has not been wetted by rain, the moisture content should be brought to field capacity before planting time by a preplanting irrigation. On soils with fairly high moisture storage, it is not desirable to attempt to replenish moisture below the third or fourth foot during the growing season. The initial storage of soil moisture in the lower depths of soil ordinarily will supply the seasonal needs of the cotton plants below the zone of principal root activity.

The main root concentrations of cotton are in the upper 2 or 3 feet in fine-textured soils and the upper 3 or 4 feet in medium- and coarse-textured soils. In humid sections that have favorable distribution of rainfall, the depth of penetration of the rains through the growing season modify the patterns of root distribution and extraction.

STUDIES OF SOIL MOISTURE have been carried out in various areas. Most of the researchers used frequency of irrigation as the method of varying the level of soil moisture or carried out their studies in pots. Such data do not permit general recommendations, but they give information on the response of cotton to varying levels of soil moisture.

F. G. Gregory and his associates, working in Egypt with long staple cotton, obtained increases of 130 pounds of seed cotton an acre by watering heavily every 2 weeks as compared to a light irrigation.

S. H. Beckett and C. F. Dunshee studied the effect of irrigation on the performance of Acala cotton in California in 1926–1930. They found that plants that were irrigated when about 50 percent of available moisture remained, showed no wilting and produced the largest plants, the greatest number of flowers and bolls per plant, the least shedding, the highest percentage of five-lock bolls, and the highest yields. Plants that were not irrigated until the soil moisture approached the permanent wilting point in the root zone started wilting by 9 a. m. and gave the lowest yield and poorest performance. Plants irrigated when wilting started by 4 p. m. were intermediate in their effects. They applied an average of 38.6 inches of irrigation water to the wettest plots and 22.6 inches to the driest plots and found that the plot yields were proportional to the amount of water applied.

J. Hamilton, C. O. Stanberry, and W. M. Wooten, working on a coarse-textured soil near Yuma, Ariz., in 1952, found that irrigating when the soil moisture tension reached 0.20 atmospheres at the 8-inch depth gave 660 pounds more seed cotton than irrigating when the soil moisture tension reached 9 atmospheres. An intermediate level of soil moisture (irrigated when the tension reached 0.6 atmospheres) gave a response about midway between the extreme treatments. The top yield in the experiment was 2,670 pounds of seed cotton an acre.

To maintain the soil moisture tension below 0.2, 0.6, and 9 atmospheres throughout the season, it was necessary to irrigate 41, 21, and 12 times, respectively. That was on a sandy soil and under extreme temperature conditions. Irrigating when the soil moisture tension reached 9 atmospheres would probably have given the greatest net returns. Increased yields because of more frequent irrigations were not large enough to pay for the increased costs.

Bert A. Krantz and K. R. Stockinger, working under similar climatic conditions on fine-textured soil in California in 1952, increased yields from 1.80 to 3.65 bales of lint an acre by

maintaining a higher level of soil moisture. The low- and high-yield treatments were irrigated when the soil moisture tension at the 16-inch depth had reached 15 and 0.66 atmospheres, respectively. An intermediate treatment (irrigated when the moisture tension reached 5 atmospheres) yielded 2.66 bales an acre. The number of irrigations required to maintain these moisture levels was 8, 10, and 17 for the low, intermediate, and high yields. Obtaining an extra bale for seven additional irrigations is profitable.

A similar experiment was conducted in 1953, but more emphasis was placed on treatments in which the soil was kept more moist. The yields ranged from 3.02 to 2.10 bales an acre for treatments that were irrigated when the soil moisture tension at 8-inch depth reached 0.33 and 6 atmospheres, respectively. The intermediate treatments, which were irrigated when the soil moisture reached 0.66 and 2 atmospheres, yielded 2.74 and 2.76 bales an acre, respectively. The treatments had adequate plant nutrients.

To maintain the moisture, it was necessary to irrigate 19, 15, 11, and 8 times when the soil moisture tension had reached 0.33, 0.66, 2, and 6 atmospheres, respectively. Three additional irrigations gave an extra 0.66 bale an acre, but 8 more irrigations resulted in an increase of only 0.26 bale. The three additional irrigations were profitable, but the value of the further irrigations was doubtful. The applications of water were not measured in the experiment. On the basis of measurements in the 1954 experiments, however, it is estimated that about 45 and 32 inches of water were applied to the 0.33 and 6 atmosphere treatments, respectively. In the experiment with frequent irrigation (every 5 days) in a soil with an ample nitrogen supply, the cotton did not become unduly vegetative and yields were not reduced.

Farmers in the humid region have considered cotton to be a dry-weather plant. The frequent short droughts never caused a complete crop failure. Even so, the actual yields often were much below the potential because of limited soil moisture at certain stages of plant growth. Damage from insects was generally considered to be less in dry weather than in wet seasons. More effective means have been developed for controlling insects in cotton. That and the greater emphasis on more efficient production have heightened interest in ways to eliminate the effects of drought by irrigating.

Lloyd Johnson, at the Alabama Agricultural Experiment Station, found that supplemental water during severe droughts increased yields but that excessive watering during wet years reduced yields. In 1950, when rainfall amounted to 12.94 inches in June, July, and August, irrigation applications totaling 7 inches caused the yield to drop from 1,328 pounds an acre to 1,053 pounds. In 1952, when 9.06 inches of rain fell in June, July, and August, the yield was increased from 1,449 pounds an acre to 2,538 pounds by 5.2 inches of irrigation water.

Results obtained at the University of Georgia showed small to very favorable increases in yield with irrigation. In 1951, when rainfall in June, July, and August was 12.37 inches, the yield of seed cotton was 2,165 pounds an acre. An additional 4 inches of irrigation in that period increased the yield to 2,538 pounds an acre. The rainfall in June, July, and August of 1952 totaled only 8.82 inches, and the yield of seed cotton was increased from 742 pounds to 2,534 pounds an acre by supplemental irrigations of 9.44 inches of water. Similar increases were obtained in the dry years of 1953 and 1954.

Billy B. Bryan, Russel Benedict, and D. A. Brown, of the University of Arkansas, reported average yields of 1 bale an acre without irrigation and 1.57 bale with irrigation in the 3 years from 1950 to 1952 at Marianna. Rainfall in June, July, and August averaged 10.29 inches those years, and an average of 5 inches of irrigation water was applied each year.

Research workers at the Delta Sta-

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tion of Mississippi State College in 1952 recorded yields of seed cotton of 2,021 pounds an acre without irrigation and 2,461 pounds when 5.15 inches of irrigation water was applied.

D. M. Whitt, of the Missouri Agricultural Experiment Station, reported yields of 1,414 pounds an acre without irrigation and 3,458 pounds with irrigation in 1953. He applied 7.43 inches of water in 4 irrigations in July and August. He reported that the cotton plant reacted to conditions of moisture stress (limited moisture) by shedding leaves, flowers, squares, and bolls.

W. P. Law, Jr., reported that in tests at Clemson Agricultural College in South Carolina in 1953 yields of seed cotton were increased 655 pounds an acre by 2 irrigations totaling 2.6 inches of water. He also observed that defoliation of irrigated cotton is more effective than in nonirrigated cotton because there is less second growth after late summer or early fall rains if the plants had ample moisture all season.

PROPER TIMING of irrigation is necessary for highest production. K. Harris and R. S. Hawkins in Arizona and Frank Adams and his coworkers in California emphasized the importance of adequate early irrigations to stimulate rapid growth before fruiting. Delaying the first irrigation after planting reduced early boll set and stimulated excessive vegetative growth late in the season.

Win Lawson conducted an experiment at Indio, Calif., to study factors that caused excessively rank growth of cotton. He found that plants that received adequate moisture throughout the season were 11 inches shorter and less rank than those for which the first irrigation had been delayed until about 11 weeks after planting. His results and other experiences indicate that the practice of delaying the first irrigation "to stress the plant and force the roots down" is not well founded.

Krantz and Stockinger investigated the effect of timing of irrigation in 1952 and 1953. They found that reducing the level of soil moisture when cotton started to fruit or when the first bolls opened up resulted in yield reductions. Reducing the soil moisture level from 0.66 atmosphere to 5 and 15 atmospheres at 8-inch depth when the first bolls formed reduced yield from 3.65 to 2.66 and 1.80 bales an acre, respectively. If the moisture level was not reduced to those levels until the first bolls started to open, however, the yield was reduced from 3.65 to 3.24 and 3.03 bales an acre.

Another experiment disclosed that reducing the soil moisture level from 0.66 atmosphere to 6 atmospheres at 8-inch depth when fruiting started reduced yields from 2.74 to 2.30 bales an acre. If the cotton was kept dry (irrigated at 6 atmospheres tension) early in the season until fruiting started and for the remainder of the season irrigated at 0.66 atmosphere tension, however, the reduction in yield was about the same, the yields being 2.74 and 2.38 bales an acre. If the reductions in soil moisture levels were made in early September (just before the first picking) yields were not lowered.

The results indicate that plants should never be allowed to become stressed until most of the bolls have set.

Field observations in the humid area and limited research data indicate that best results are obtained from irrigations applied during the fruiting stage. Winter rains usually replenish the soil moisture supply throughout the root zone. Tillage and planting operations often cause the plowed layer to dry out to such extent that seed germination is poor when rains do not closely follow the planting operation. A light irrigation after planting often can end germination troubles in short dry spells.

Roots of cotton plants penetrate rapidly into the soil after germination. Usually there is little need for irrigation until plants reach the fruiting stage. Then the number of needed irrigations will depend on the distribution of rainfall. No set rules can be laid down because rainfall is erratic.

Results previously quoted from the

Alabama Agricultural Experiment Station indicate that cotton yields best if there is neither excessive moisture nor serious wilting. Withholding water until the wilting stage is approached and then restoring the soil moisture appears to be the most efficient method of supplying the water needs of the cotton plant when rainfall is deficient. The irrigation schedule must be gaged to prevent appreciable wilting.

The first one or two applications of water in dry seasons cause rapid germination of weed seeds. Excessive weed growth may follow when the watering is done after cultivation is completed. Irrigation schedules and operations to control weeds should be managed with that in mind.

FERTILIZATION AND MANAGEMENT may influence the irrigation needs of cotton.

J. Hamilton and C. O. Stanberry at Yuma, Ariz., investigated the effects of varying rates of nitrogen fertilizer and different plant spacings on the need of cotton for irrigation. They found that the effect of increasing moisture levels was small or negligible when the amount of nitrogen was low. When adequate nitrogen was available, however, the response to moisture was appreciable, and the best response to nitrogen was obtained in the wet treatment, thus showing the importance of getting the optimum combination of factors. Effects of spacing were additive to the soil moisture responses. The wider spacing produced the most lint but the effects were the same at all moisture levels.

In the Imperial Valley, Krantz and Stockinger did not get any additional response to soil moisture at the higher levels of nitrogen. Yield increases from additional nitrogen were the same for all levels of soil moisture. As the high rates of nitrogen and water used were more than ample for maximum yields, it seems that there was no interaction effect on the fine-textured soils.

At the Mississippi Delta Station in 1952, nitrogen was applied at the rates of 60, 90, and 120 pounds the acre at planting in plots with and without irrigation. Yields of seed cotton without irrigation were 2,317, 2,465, and 2,727 pounds an acre, respectively, for those rates. Irrigation increased the yields to 2,748, 3,040, and 3,314 pounds an acre for the same rates of nitrogen. Irrigation increased the yields in all instances and also increased the response to nitrogen fertilization.

M. E. Bloodworth and his associates at Weslaco, Tex., studied the effect of four levels of irrigation at three plant spacings. They found that the closer spacings increased yields in high-moisture plots and lowered yields in the dry plots. They also obtained the greatest plant growth, lint yields, and largest root growth in the wetter plots.

Problems of insect control are not unduly worsened by moderate irrigation. The extra fruiting of plants with ample soil moisture, over those in dry soil, offsets the tendency toward increased activity of the boll weevil and other insects caused by the greater supply of moisture.

FIBER AND SEED PROPERTIES are less influenced by the level of soil moisture than is yield. Some characters, however, are altered by soil moisture stresses.

P. J. Lyerly and his associates at the Texas Agricultural Experiment Station at Yaleta found the following increases between their lowest and highest moisture levels: Yield, 98 percent; boll size, 16 percent; seed index, 20 percent; lint index, 8 percent; mean length, 14 percent; and upper half mean, 10 percent. Lint percentage and fiber strength decreased 8 and 12 percent, respectively. D. G. Sturkie, of the Alabama Agricultural Experiment Station, and W. P. Law, of Clemson College, found similar trends. Sturkie also observed that with adequate moisture the fibers were more mature and heavier and the oil content of the seed was higher than in cotton grown with deficient soil moisture. His investigations included

studies of soil type, soil preparation, fertilizers, and organic matter, and he concluded that the moisture condition of the soil was the most important factor affecting fiber properties.

FOR MAXIMUM PRODUCTION the cotton plant should never be subjected to stress. One should irrigate according to the needs of the plant and not by the calendar. A deficiency of soil moisture can be detected visually first by a dark, bluish tinge of the plant foliage and later by a wilting of the leaves. The grower should inspect the cotton plants in the drier spots of the field and use them as indicators of irrigation needs. He should start irrigating when the plants start showing a need for water. Irrigation should be continued until all the bolls that are expected to mature are set. Later irrigations in the fall usually will cause undesirable vegetative growth.

A deficiency of moisture is most common during the fruiting period in the humid region. Supplemental irrigation often will increase yields, and eliminate the hazard of failure due to drought.

To reap the maximum benefits from his irrigation investment, the farmer should use good seed of adapted varieties, fertilize properly, control weeds and insects, and use other good management practices.

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The Irrigation and Culture of Rice

C. Roy Adair and Kyle Engler

Upland rice, which is not irrigated, and paddy, or irrigated, rice require different varieties and different cultural methods.

All of the commercial rice in the United States is grown under controlled irrigation. Several systems of controlled or uncontrolled irrigation are used in various countries to supply the water needed for the development of the rice plant.

Upland rice is grown in areas where rainfall is heavy during the growing season. Much of the rice grown in Central America and South America and in many countries in Asia is produced under upland conditions. Upland rice also is grown for home use in small fields, totaling fewer than 3,000 acres, in the Southeastern States.

A limited acreage of "providence" rice is grown in Louisiana and elsewhere in the Southern States. Field levees are constructed as for irrigated rice, but rainfall supplies the needed water. Fairly satisfactory yields are produced in seasons of uniformly high rainfall, but average or dry seasons mean low yields.

Floating rice is grown in southeastern Asia where streams overflow during the growing season. Some especially adapted varieties are sown before the flood season. The waters rise slowly, and the fields remain inundated for several weeks. Meanwhile the plants elongate rapidly as the depth of the water increases. The culms are weak but are supported by the water. When the water recedes, the plants lodge, but enough straight growth remains so that the panicles are off the ground and seed is produced. Rice produced in that way must be harvested by hand.

Land suited to rice usually is rather level and has a definite drainage pattern. In the Philippines and elsewhere in southeastern Asia, however, rice is grown on terraces in mountain regions, where sometimes the entire mountainside has been converted into a series of rice paddies. Spillways permit the water to flow down from one terrace to another.

In the United States the irrigation water is diverted from streams or is pumped from rivers, bayous, wells, lakes, or reservoirs. The water is delivered into field levees, which are built on the contour and keep the field submerged at a fairly uniform depth.

RICE GROWING in the United States started in the 17th century near Charleston, S. C. Rice soon became an important crop along the tidal streams in the South Atlantic coastal area. The fields along the streams were divided by drainage ditches and levees into plots of about the same level. The levees were constructed from the earth taken from the ditches. The small fields were next to canals, which carried the water from streams. The canals also connected small streams, formed dividing lines between plantations, and provided for barge transportation during planting and harvest. Floodgates, located above the salt-water line in the streams, controlled the flow of water into the canal. The gates were placed so that water flowed into the canals at high tide and was shut off at ebb tide. The gates could be opened at low tide to drain the fields.

New settlers, coming in after 1865, attempted to grow rice on the prairie in southwestern Louisiana.

They found that rice grew very well there, and that the sluggish streams, called bayous, provided plenty of water for irrigation. The problem was to get the water to the higher lands. The first attempt was to dam up small drainage areas and collect water during the winter. The water was pumped to the field by small pumps driven by steam engines. These systems were improved, until in 1894 the first large irrigation plant was established on

Bayou Plaquemine, about 2 miles from Crowley, La. It first used a vacuum-type pump, which failed in midsummer. The next year a centrifugal pump was installed, but it did not have enough capacity to deliver the water needed for the entire acreage. A larger centrifugal pump, installed in 1896, delivered 5,000 gallons of water a minute, enough for the planted acreage. Many pumping plants were installed on the streams in southwestern Louisiana and southeastern Texas the next few years. Some pumping plants in operation in 1901 delivered up to 45,000 gallons a minute.

THE WATER REQUIREMENT for rice is rather high, because the fields are submerged for 3 to 5 months.

In California 3 to 8 feet are needed each season. The requirement in Arkansas and Louisiana is 1.5 to 3 feet. The amount of irrigation water required is least in places where the subsoils are relatively impermeable and the seasonal rainfall is high. The normally abundant rainfall cuts the pumping requirements in the rice sections of Arkansas, Louisiana, and Texas, but unusually heavy rainfall may cause breaks in the levees and serious losses of water.

More than 40 percent of the 1953 rice acreage in the United States was irrigated from wells. About 90 percent of the 485,000 rice acres in Arkansas, 40 percent of the 604,000 acres in Louisiana, and 20 percent of the 573,000 acres in Texas, 10 percent of the 394,000 acres in California, and most of the 75,000 acres in Mississippi were irrigated from wells.

Pumping from bayous supplies most of the surface water in Louisiana and Texas. Diversion from large streams is the main source of water in California. The main surface water supply in Arkansas is from reservoirs that range in size from 20 acres to more than 4,000 acres and are filled during periods of high runoff.

Heavy, concentrated pumping has seriously lowered the ground water level in some parts of Arkansas, but other sources of irrigation water are being developed. The recharge of ground water through wells has been considered.

Diesel engines came into common use for pumping water after 1919.

Convenience, low labor requirements, and reasonable initial and operating costs have since caused a shift to electric power for irrigating rice. About 1,800 irrigation installations, nearly 50 percent of the total, were powered by electricity in Arkansas in 1955. In Louisiana, of a total of 1,061 wells, 450 were powered by diesel engines, 212 by natural gas, 105 by electric motors, and the remainder by other units.

The efficiency of the pumps has improved rapidly, so that outlays for electricity have dropped. Pump bowls ordinarily had an efficiency of about 20 or 40 percent in 1915. Modern pump bowls of suitable design have efficiencies of about 83 percent.

Costs of electric power for irrigating rice in Arkansas ranged from 4.68 to 11.24 dollars an acre in 1954. Fixed or overhead costs averaged about 3.75 dollars an acre. The electric rates for rice irrigation are lowest for pumps that operate continuously during the season, but it may be advantageous to pay slightly higher rates in order to have a larger flow of water during some periods and to reduce the time expended in irrigating. A flow of 5 gallons a minute an acre delivers the average of 22 acre-inches required in slightly more than 80 days, while 7.5 gallons requires a little less than 60 days. The average well flow on Arkansas rice farms has been estimated at about 7.1 gallons a minute an acre. Farm experience thus indicates a preference for more than the minimum.

The water is conveyed from the pumps, streams, or reservoirs in canals, from which it is diverted into laterals, field ditches, and finally the field checks, or levees. Those structures should be located by a competent engineer and be of proper size to provide water when and where it is needed.

When the rainfall is below normal in the gulf coast of Louisiana and Texas, the water level in the streams that supply irrigation water often is so low that brackish water encroaches from the Gulf. The concentration of chloride salts may become so high that the yield and quality of the rice is reduced or the crop ruined.

Water that contains more than 35 grains of salt a gallon (600 parts per million) should not be used to irrigate young rice if the soil is dry and if the water is to remain on the field. Rice watered continuously with water containing 35 and 75 grains of salt a gallon (600 and 1,300 parts per million) was reduced in yield about 25 and 70 percent, respectively, and the rice was of lower quality than when water containing 25 grains a gallon was used. The rice plant can tolerate higher concentrations of salt, in the later stages of growth, although very high concentrations may kill the plants or make them sterile. The Blue Rose variety is more tolerant to salt than some other varieties and has made satisfactory yields when the water contains salt concentrations of 75, 150, 200, and 250 grains a gallon in the tillering, jointing, booting, and heading stage, respectively. Some of the newer varieties probably would be damaged seriously by those amounts of salt.

If a field has been watered with fresh water and the supply is then replenished with salt water, the damage will be less than if the salt water is put on dry soil. The reason is that the salt is more concentrated in the dry soil and more of it moves into the root zone, whence it is taken up by the plants. Rice grown on clay soils may not be injured by salt water to the same extent as on lighter soils, because less water is used and less is lost by seepage.

About 3 tons an acre of salt are added when water containing 50 grains of salt a gallon is used for the whole growing season. The accumulations of salt over the years may deflocculate the soil, so that stickiness, compactness, and impermeability increase. The deflocculated soil is hard to cultivate and produces low yields.

Well water, used to irrigate a large part of the rice acreage in Louisiana and Arkansas, usually is low in chlorides. In the lower basin of the Vermillion River in Louisiana, however, salt water encroaches on the Chicot Reservoir when the river is intruded by salty water.

Water from shallow wells sunk into Quaternay beds in Arkansas contains 75 parts per million of calcium and 22 parts per million of magnesium. Soils that have been irrigated for many years with this well water have increased in pH ratio from about 5.0 up to as high as 8.0. That change from a highly acid to a highly alkaline reaction is due to the annual addition of about 1,500 pounds an acre of limestone equivalent. The increase in available calcium and magnesium lowered the availability of phosphorus in the soil. If a new source of water is obtained that is low in dissolved minerals, those changes may be reversed.

Rice has been grown in order to reclaim saline or alkali lands in California. It is successful when the water is appreciably lower in dissolved minerals than is the soil, the soil is relatively permeable, and drainage is adequate. Crops that are not salt-tolerant can be grown on the alkali soils after 2 or 3 years of rice.

The temperature of the irrigation water is important. The temperature may be too low early in the season and too high late in the season for maximum emergence of rice sown in the water. Germination is retarded when the temperature of the water is below 70° F. Roots develop poorly when the temperature is above 85°, perhaps because of the low oxygen content of warm water. The temperature of the water from shallow wells in Arkansas and from streams in California is usually 65° F. or lower. When such cool water goes directly into the field, the rice growing near the water inlet usually is retarded. Such "cold water" rice may ripen 7 to 10 days later than

the rice in the rest of the field, and the difference interferes with harvesting. The way to avoid that condition is to hold the water in a warming basin or to have several inlets to the field. The water from deep wells in Arkansas and from the streams, lakes, and reservoirs in the South usually is warm enough for rice.

WATER IS DELIVERED usually to the highest point in the field by canals or pumps. It passes into successively lower paddies through openings or metal checks in the levees. Metal checks provide permanent control of the maximum height of water in each paddy. Field levees must be properly spaced and on the contour to provide uniform irrigation and complete drainage. Levees are spaced at a difference of about two-tenths of a foot elevation between adjacent levees. Smoothing the land before surveying results in more accurate surveying, more uniform irrigation, and better drainage.

Either levee disks or pusher-type machines form levees with sloping sides and high enough to hold water 4 to 6 inches deep on the subfields or paddies without overflowing into the next lower paddy. Low, sloping levees reduce production costs because they can be seeded and thus produce considerable rice while reducing weed growth.

Two general methods of seeding and irrigating rice are practiced in the United States. One is to drill the seed in the soil; submergence follows. The other is to broadcast the seed in the water.

Most of the rice in the Southern States is drilled or is sown with an endgate seeder and covered with a disk or harrow. The soil is then irrigated lightly if moisture is needed for germination and growth of seedlings. Later the soil is submerged when the plants are 6 to 8 inches tall.

The seedbed is prepared by plowing with a moldboard or disk plow in the fall, winter, or early spring, followed by disking and harrowing, and sometimes the use of a heavy plank drag to break the clods. Heavy soils, such as Sharkey or Beaumont clay, usually are dry by the time the land has been prepared and seeded so that it becomes necessary to irrigate to germinate the seed unless rain comes soon after seeding. The field must be drained after the early irrigation, because rice seed that is covered with an inch or more of soil will not germinate in standing water. This practice, however, also provides ideal conditions for the germination and growth of weedy grasses.

Experiments started in 1914 on new rice lands in California showed that the best yields were obtained when the land was submerged to a depth of 6 to 8 inches about 30 days after the rice seedlings emerged. This method, however, favored the invasion and increase of weedy grasses, particularly barnyard grass (*Echinochloa* species), and therefore was not suited to old rice lands. Experiments in Arkansas demonstrated that a heavy infestation of grass reduces the yield of the rice by 50 percent or more. Water-seeding methods were developed to control the weedy grasses.

The seeding of rice in water was started in California as a way to control barnyard grass. Low spots covered with water when a field was being drilled often were sown by hand broadcasting, and such spots were observed to be relatively free from barnyard grass. Experiments in seeding rice in the water about 6 inches deep demonstrated that many grasses could be controlled in that way, and good stands of rice and high yields could be obtained. The rice germinates and emerges through 6 inches of water, whereas the grasses seldom get to the surface of the water. At first the rice was sown with a broadcast seeder. Broadcasting in water with an endgate seeder stirs up mud, which makes it hard for the driver to follow a straight line. The airplane is more satisfactory for sowing submerged land. The airplane operator is guided by flagmen,

one at each end of the field, who pace off the distance (about 30 feet) that the plane can sow in one trip across the field.

Airplane seeding was attempted first near Merced, Calif., in 1929, for reseeding a field in which the rice had been destroyed by mud hens. A fair stand of rice and a satisfactory yield were obtained. Several California growers seeded their rice with an airplane in 1930. Now airplane seeding is the common practice among growers in California. Experiments with water seeding in Arkansas and other Southern States developed modifications, which were adapted to the other areas.

The prevailing method of growing rice in California is to plow the land in early spring to a depth of 4 to 6 inches and allow the soil to dry for 7 to 10 days. A satisfactory seedbed can then be prepared by harrowing twice and floating once with a heavy plank drag. The field levees are then put up, the floodgates put in place, and the field flooded to a depth of about 6 inches. Seed that has been soaked for 36 to 48 hours is then sown with an airplane at the rate of 135 pounds of seed an acre. The field is kept submerged to a depth of 5 to 7 inches until the rice is ready to drain before harvest. Preparing the seedbed when the soil is dry gives better control of some of the aquatic weeds and grasses that cannot be controlled by flooding and retards the growth of algae (green scum) on the surface of the water.

In the water-seeding method in Arkansas, the land usually is plowed in winter, and the seedbed is prepared by disking 2 or 3 times and then harrowing. Frequently the soil also is tilled to a depth of about 8 inches with a field cultivator to provide space for the application of cool irrigation water that contains oxygen, which is necessary for early root development. The water below the surface of the soil remains cool and retains considerable oxygen, whereas the surface water is warmed by the sun, and much of the oxygen escapes. The levees are completed after the soil is worked with the field cultivator, and the field is then cultivated with a springtooth harrow, which leaves shallow furrows and ridges that prevent drifting of the seed. The floodgates are then put in, the field submerged to a depth of 4 to 6 inches, and the rice sown from an airplane. Seeding is done as promptly as possible, as poor stands usually are obtained when the water has been on the field longer than about 4 days before seeding. The seeding rate is 100 to 110 pounds of dry seed an acre. The water is usually drained after 5 to 6 weeks for the control of the rice water-weevil and to provide dry soil for top dressing with fertilizer.

The water-seeding method as practiced on heavy clay soils in Texas and other Southern States consists of plowing and disking the land to kill vegetation, but the surface is left rough. The levees are then put up and the field is irrigated enough barely to cover the land. The flooded field is then cultivated with a light disk or heavy spike tooth harrow. The soaked seed is sown immediately from an airplane. Sometimes a shallow flood is left, but usually the excess water is drained off the field after seeding and the seeds are covered with a thin film of mud. Germination of the presoaked seed is rapid. As soon as the seedlings emerge, a shallow flood of water is added to fields that were drained after sowing. The depth of water is increased gradually up to 5 to 7 inches as the seedlings elongate. The water may be drained 1 or 2 times during the growing season to control insects or to apply fertilizer.

Correct timing of irrigation and drainage may help to control certain insects. The root maggot has reduced yields up to 29 percent in some areas, and increases of 11 to 27 percent in yield have been obtained by draining the field when heavy pruning of the rice roots by the maggots is evident. That usually occurs about 17 to 28 days after the field is first submerged.

The practice, however, makes an ideal breeding place for rice-field mosquitoes (*Psorophora confinnis* and *P. discolor*). They lay their eggs on the soil from which water has been drained. The eggs hatch when the soil is again submerged. The southern corn rootworm, chinch bugs, sugarcane beetles, and the southern grass worm, which often are serious pests in some places, often can be controlled somewhat by submerging the field when seedlings are attacked or by holding the water on the field as long as possible when the rice is attacked as it is nearing maturity.

Several diseases of rice can be controlled or the losses from them can be reduced by using the correct irrigation methods. Straighthead is a nonparasitic disorder characterized by failure to set seed, usually accompanied by a distortion of the palea and the glumes. Straighthead sometimes is destructive in the Southern States on soils high in organic content. It occurs most frequently on sandy, loamy, or mixed soils but rarely on clay soils. Effective control is obtained by draining the field just before the panicle bud forms—usually 6 to 8 weeks after emergence, depending upon length of growing season of the variety. The field is flooded again as soon as the soil is dry.

Stem rot, a fungus disease, first appears in midsummer as small, discolored areas on the sheaths of the rice stem near the water line. The most satisfactory method of control is to drain the water from infected fields before the infection reaches the culm. Water should then be added from time to time to keep the soil saturated but not submerged. Such treatment may result in reduced losses from lodging, but a slight reduction in yield is usual where infection is light. Such irrigation should not be practiced unless infection is heavy.

Blast, caused by the fungus *Piricularia oryzae*, has caused losses in yield in the Southern States from time to time. Usually the most obvious and damaging phase of the disease is the infection of culms and panicles after the plants have headed. Infection also occurs in the seedling stage and causes a reduction in stand before the field is submerged, but then injury may be reduced by submergence of the land as soon as the leaf spots become evident.

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Growing 100-Bushel Corn With Irrigation

H. F. Rhoades and L. B. Nelson

Corn cannot be grown profitably without irrigation in the arid sections of the West. Irrigation changes corn from a marginal to a profitable crop in semiarid areas. It removes the ever-present hazard of drought in the subhumid area and the humid East.

Corn yields greater than 150 bushels an acre have been obtained in experiments under irrigation at several places in dry sections of the West. Such yields were obtained only by the use of the best combination of practices, but farmers in those areas can expect to improve yields by adopting similar practices.

Benefits from irrigating corn vary from year to year in the subhumid and humid sections. Experiments at the Redfield Development Farm in South Dakota showed increases in yield due to irrigation of 117 and 27 bushels an

acre following alfalfa in years of below normal and above normal rainfall, respectively. At Athens, Ga., increases resulting from irrigation ranged from less than 6 bushels an acre in years with nearly ample rainfall to 64 bushels an acre in years of droughts. Such results suggest that farmers in the subhumid region can benefit each year and that farmers in the humid regions can benefit most years from irrigating corn. Soil-management practices for high-level production must be adopted, however, to take full advantage of the added water.

Fewer than 1 million acres of corn were irrigated in the United States in 1949—more than half of it in Colorado and Nebraska. It seems likely that the irrigated corn acreage will expand as new lands are irrigated.

FURROW IRRIGATION is the most common method of applying water for corn in the West. It may be used to advantage on some farms in the East. An essential is that the land be prepared so that water can be uniformly distributed. Nearly all fields require some leveling to insure efficient furrow irrigation.

Furrow irrigation is accomplished by running water down the slope in furrows between the rows. On slight slopes, the corn is planted so that the furrows are parallel with the prevailing slope. On steeper slopes, the rows may be placed somewhat across the prevailing slope or nearly on the contour. Distribution of the water into the furrows from head ditches, flumes, or gated pipe can be accomplished by following the procedures described on pages 258 to 266. Plastic siphons over the banks of the head ditches or spiles through the banks are usually more desirable than cuts through the banks.

The distance between field ditches or the length of run that will provide uniform distribution of water are determined by the permeability of the soil, the slope, and the size of the stream. A satisfactory distribution of water may be obtained with long runs of 1,000 to 1,300 feet on soils of slight slope with moderately low permeability. On other soils with a high permeability or with steeper slopes, the length of run may be less than 600 feet. Shorter runs may be required on some fields the year after a legume crop than the year following corn or small grain.

A stream size should be used in furrow irrigation that will give a uniform distribution, a minimum runoff at the end of the furrow, and a minimum loss of soil by erosion. It may be desirable to use a large stream until the water gets to the end of the furrow and then reduce it so that the runoff will be only a small percentage of the water applied.

SPRINKLER IRRIGATION is the most common method of irrigating corn in the East, and is being used on a considerable acreage in the West. The most desirable type for corn seems to be portable, quick-coupling, aluminum pipe with rotating head or circular spray sprinklers. As corn usually is grown in rotation with other crops, stationary systems are not suitable.

It is particularly important to select sprinklers to fit the conditions on individual farms. They should apply water at a rate comparable to the infiltration rate of water into the soil. Excessive rates waste water and may cause erosion.

Portable sprinklers are hard to move in cornfields. Several methods have been proposed to make it easier to use sprinklers in high corn. One is to intercrop wide-row corn with grasses and legumes. The sod between the wide rows provides for setting up and moving the pipe. Another method consists of interspersing strips of corn with strips of sod or strips of a row crop, such as soybeans, and making the sprinkler installations on the low-growing crops.

IRRIGATED CORN ordinarily uses 16 to 25 inches of water during the growing season, although amounts up to 33 inches and as low as 12 inches have been reported.

Many factors influence the use of water by corn. Among them are climate, length of growing season, stage of growth, total growth, irrigation practice, stand, and fertility of the soil. Physical properties of the soil, which control water movement, water storage, and air movement, have an influence also. Disease and insect pests affect growth and therefore the use of water. Temperature, humidity, and wind movement affect the transpiration of water and evaporation from the soil surface.

Evaporation of water from the soil surface and the water use by corn are intensified by frequently wetting the soil, because moisture in the surface evaporates more readily than moisture at greater depths. Frequent irrigations or rains or a combination of both accordingly will tend to increase consumptive use of water through greater evaporation. High humidity accompanying rainfall, but not irrigation, may offset that effect somewhat.

A single corn plant in full leaf may transpire 32 quarts of water in a week. The amount of water transpired depends on the stage of development of the plant and the climatic factors. It is least when the corn plant is small, increases to a maximum at about silking time, and continues at a fairly high rate until near maturity. The average consumptive-use rates may be 0.30 inch a day for irrigation periods of 15 to 20 days during the second half of July and most of August. For shorter periods, the rate may be as high as 0.4 inch a day during hot, windy weather.

Any factors, such as irrigation practice, stand, and soil fertility treatment, that promote growth will also increase the consumptive use of water by corn. Even so, one can improve the efficiency with which corn uses the water in terms of pounds or bushels of crop produced by a given amount of water.

Six irrigations at Mitchell, Nebr., that maintained a high level of soil moisture throughout the growing season gave a yield of 153 bushels an acre from 21.4 inches of water, or 7.1 bushels an acre-inch of water. On the plots where a high level of soil moisture was maintained only during the stage of growth just before tasseling through silking with three irrigations, the yield was 144 bushels an acre from 15.6 inches of water, or 9.2 bushels an acre-inch of water.

Less water is needed to produce a unit weight of plant material on highly fertile soils than on soils with a low level of fertility. Near Lincoln, Nebr., for example, corn grown on soils of low and high fertility required 550 and 392 pounds of water, respectively, to produce 1 pound of dry matter. Ten inches of irrigation water applied during the growing season at Arapahoe, Nebr., resulted in a yield of 108 bushels an acre where an adequate supply of nitrogen fertilizer was applied and a yield of 68 bushels an acre when it was not applied.

Moisture supply at different periods greatly influences the growth characteristics of corn. A deficiency of moisture in the soil during early growth slows down vegetative growth, delays silking and tasseling, and delays maturity. If the deficient moisture supply is alleviated by tasseling time and optimum moisture is maintained throughout the rest of the growing season, yields are likely to be reasonably good.

A deficiency of moisture during tasseling and silking sharply lowers the yields. The greatest need of corn for high soil moisture is during that period. A depletion of available moisture for 2 days and 6 to 8 days during the tasseling period in Washington cut yields 22 and 50 percent, respectively. Three irrigations that maintained a high moisture level from tasseling through silking in Nebraska produced 144 bushels an acre, but three irrigations before tasseling produced 118 bushels an acre.

From a moisture deficiency after tasseling and silking, the degree of reduction in yield is related to the stage of maturity of the grain at the time of the moisture depletion. Following matu-

rity (hard-dough stage), soil moisture can be depleted without effect on yield. Moisture deficiencies after silking have little effect on vegetative growth.

Moisture deficiency throughout the growing season results in stunted plants having short internodes, more root growth in relation to top growth, poor leaf growth, delayed silking and tasseling, delayed maturity, and small, poorly filled ears. In an experiment in Nebraska, a yield of 69 bushels an acre was obtained where moisture was deficient most of the growing season, compared to a yield of 153 bushels when moisture was adequate.

The depth of water removal by corn is important to the irrigator. Corn roots first obtain water at a shallow depth immediately beneath the plant. Moisture removal then extends laterally until most of the available moisture in the plow layer is removed. After that, water is depleted from successively lower depths. The depth of moisture removal, however, is influenced by the characteristics of the subsoil. In permeable soils, corn may remove moisture to depths of 5 to 6 feet, according to the irrigation practice. With subsoils of low permeability, root penetration and moisture removal may be limited to the upper 2 feet of soil.

The progressive removal of water from successively lower depths of a permeable, very fine sandy loam soil is illustrated by an investigation in Nebraska, where there was no irrigation during the growing season. About 65 percent of the available water had been removed from the surface 6 inches of soil by July 4. All of the available moisture in the top 6 inches was exhausted by July 14, from the upper 30 inches by July 31, and from 42 inches by October 13. At the latter date, approximately 95 percent of the available water had been removed to a depth of 66 inches.

Irrigation or rainfall, on the other hand, greatly influences the pattern of water removal. Rooting is shallower when plenty of moisture is available, and less water is obtained from lower depths. In Nebraska, where a high level of moisture was maintained through the growing season on a permeable soil, about 95 percent of the water used by the corn was obtained from the upper 3 feet of soil and 89 percent from the upper 2 feet. Without irrigation, only 63 percent was obtained from the upper 3 feet and 53 percent from the upper 2 feet.

Frequency of irrigation will vary with the water-holding capacity of soil, the amount and distribution of rainfall, and the stage of plant growth. No ironclad set of rules can be given, but the following points may help.

Try to start the season with the soil moist to the maximum depth that corn roots will extend during the year. During most seasons in humid areas, overwinter precipitation will accomplish this. An irrigation will frequently be necessary in drier regions. It can be applied in fall or early spring.

Watch the soil moisture and plant symptoms. Irrigate if the corn exhausts the soil moisture in the top 12 inches before tasseling or shows temporary leaf curling or wilting. If the root zone has been replenished before planting, this irrigation may not be needed until after the last cultivation, at which time the corn is drawing heavily on the soil moisture. Sandy soils in drier areas may require an earlier irrigation.

Do not let the corn suffer from drought any time during the pollination period. Unless rainfall is plentiful and the soil is moist throughout the root zone, irrigate just before tasseling. It may be the most beneficial irrigation of all. One or two more irrigations may be required before silking and pollination is completed to maintain a high level of soil moisture. More irrigation will be required on sandy soils.

After pollination, irrigate whenever the moisture in the root zone becomes depleted. Watch the soil and the plant. If leaf curling or wilting starts, the corn must be irrigated. Corn preferably should not be allowed to reach

the temporary wilting stage. Irrigations after the hard-dough stage will have little or no effect on yield.

The frequency of irrigation for corn ranges from one irrigation every 5 to 7 days in the arid Southwest to none in the humid States in the East. Many western farmers tend to irrigate oftener than necessary. In several western areas, for example, three or four irrigations properly spaced have been as effective as 2 or 3 times as many. Droughts during the growing season determine the frequency of irrigation in the East. The best rule to follow is that of irrigating when the soil is dry. Do not wait for the next rain, and do not depend on frequent small showers to supply the moisture needs.

Apply enough water at each irrigation to fill the potential root zone to field-capacity wetness. The amount to apply depends on the water-holding capacity of the soil, the depth of the root zone, and the depth to which moisture has been exhausted. The amount may range from 2 inches on sandy soils to 6 inches on clay loam soils during the height of the growing season.

During the critical period just before tasseling and through pollination, less water may be needed in one irrigation, because frequency and timing are of primary importance. The soil should not be allowed to dry out to the extent permissible at other times during the growing season.

Furrow irrigation will deliver to the root zone 40 to 75 percent of the water applied. It is therefore necessary to add more water to the field than the amount necessary to fill the root zone to field-capacity wetness. If the irrigation efficiency is 50 percent and the water needed is 3 inches, for example, 6 inches of water must be applied. Because sprinkler irrigation is generally more efficient than furrow irrigation, less water needs to be applied than if irrigation is by furrows.

The number of corn plants on an acre must be increased under irrigation to get high yields. It does not pay to eliminate water as a limiting factor in corn production or improve the method of irrigating and then have other factors limit yields. Most profitable returns from irrigated corn result only when all practices are geared for high production. Proper adjustment of corn stands is necessary to make the best use of added water.

If single-ear hybrids are used, final stands of not fewer than 14,000 plants an acre are essential. Stands ranging from 17,000 to 19,000 plants an acre often will give maximum yields. Still thicker stands sometimes are reported as desirable. Usually stands exceeding 17,000 to 19,000 plants are hazardous, because the tendency to barren stalks, stalk breakage, and small or undeveloped ears is increased.

If prolific or double-ear hybrids are used, final stands should not be fewer than 10,000 plants to the acre. Stands of 12,000 to 13,000 plants frequently produce the best yields, but still higher stands become hazardous.

Planting rates must always exceed that of the final stand wanted. For example, 16,500 kernels usually must be planted to obtain a stand of 14,000 plants, and 21,200 kernels must be planted for 18,000 plants. Rows may be spaced as close as 30 inches apart, but 36-, 38-, and 40-inch row spacings are common.

When thicker plantings are used, great care must be given to assure an adequate supply of plant nutrients to support the additional plants.

Soil fertility must be maintained at a high level under irrigation. Deficiency of any one nutrient element can erase the benefits derived from proper irrigation and increased stands.

Nitrogen is the element most frequently deficient. The use of nitrogen fertilizers at adequate rates is an essential part of irrigated corn production. Nitrogen derived from legumes and manure can help to meet the nitrogen needs, but they should not be relied upon to meet the full nitrogen requirement of irrigated corn.

The amount of nitrogen fertilizer to apply varies with the past cropping and fertilization practices. The farmer will do well to rely on the fertilizer recommendations made for his own locality. He may keep in mind that about 2 pounds of nitrogen applied in a fertilizer is required to produce a bushel of corn. Thus, if he can grow 50 bushels of corn an acre without added nitrogen and desires to aim for 110 bushels under irrigation, he will need to apply about 120 pounds of nitrogen to the acre. Experiments usually show that irrigated corn gives most profitable responses to nitrogen rates from 80 to 160 pounds the acre.

Nitrogen may be applied to irrigated corn by any of the methods recommended for nonirrigated corn. Leaching of the nitrogen fertilizer out of the root zone of sandy soils is a problem. To avoid serious losses on such soils, it is often desirable to make 2 or 3 separate applications.

Nitrogen fertilizer may also be applied in the irrigation water any time an irrigation is made, even after the corn is too high for ordinary side dressings. Uniform distribution is best obtained under furrow irrigation by applying part of the water without fertilizer and then applying about one-half inch of water containing the fertilizer.

Nitrogen fertilizers that can be applied in the water include anhydrous ammonia, aqua ammonia, nitrogen solutions, ammonium nitrate, sodium nitrate, ammonium sulfate, urea, and ammonium phosphate. Accurate metering of the material into the water is desirable. Several types of metering equipment are available commercially and some can be built by the farmer.

As to the sprinkler application of dissolved nitrogen salts, it seems that no damage from leaf burning would result, because of the high dilution. Any such danger could be lessened by running fertilizer-free water through the sprinklers for a time following the application of fertilizer. Flushing the system with fertilizer-free water also would prevent corrosion. Anhydrous ammonia or ammonia in solutions cannot be applied through sprinklers because of losses from volatilization.

Equal care must be taken to supply other nutrients when they are needed. Phosphorus and potassium frequently are deficient in the humid region and should be applied in rates to meet the needs of a high-yielding corn crop. In sub-humid and drier regions, the potassium supply is generally adequate, but phosphorus may be deficient in some soils. In the West and parts of the South, zinc may be needed. Most States provide a soil-testing service for determining the need for phosphorus, potassium, and other elements and for recommending methods of application.

There seems to be no advantage to applying fertilizer containing phosphorus, potassium, or minor elements for corn in irrigation water. Phosphorus fertilizer particularly should be applied early, because the needs of corn for phosphorus is greatest while the plant is small. An application of phosphorus fertilizer in the irrigation water would ordinarily be too late for greatest benefits.

ADAPTED HYBRIDS are also essential to high-level production under irrigation. They must utilize the full growing season, withstand thick planting, and respond to high levels of fertility. Some hybrids are outstanding in those respects, but others perform poorly. A hybrid that performs best under average conditions of stand and fertility will not necessarily perform equally well under conditions of thick stands, high fertility, and optimum moisture.

GOOD TILTH also is necessary. The soil must be porous enough to permit ready movement of air and water into the surface and subsoil so that fairly deep rooting may occur. Most soils can be maintained in a satisfactory tilth by using manures, crop residues, a rotation including legumes and grasses, and cover crops.

Some soils are poorly adapted for irrigated corn regardless of the practices used to improve tilth. Soils with slowly permeable subsoils or pans that cannot be improved through tillage or other treatment will mean shallow rooting and poor penetration of moisture or will have such poor drainage that salts accumulated from the irrigation water cannot be removed. Extremely sandy soils are not adapted to irrigation because only small amounts of water can be stored in the soil and too frequent irrigations are required.

UNDER CORN, the soil is usually kept clean of weeds and vegetation. Therefore the soil is subject to surface sealing, which lowers the rate of infiltration of water. Sometimes the infiltration rate is so slow, less than 0.2 inch an hour, that it is hard to obtain sprinklers whose application rates are low enough to prevent undue loss from runoff. Rather than use sprinkler irrigation on such soils, it is better first to correct the condition by incorporating crop residues into the surface or by rotating with grasses and legumes.

The farmer must aim for top yields every year. Irrigation costs money, and it will pay only when high production is achieved. Under most conditions, the farmer should aim for 100 or more bushels of corn an acre and adjust his practices—proper irrigation, adequate fertilization, good adapted hybrids. good tilth—accordingly.

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The Irrigation of Sugar Beets

Jay L. Haddock

Sixty percent of all the refined sugar produced in the United States is obtained from sugar beets grown under irrigation. About 15 percent of the beet sugar we produce is obtained without irrigation. The nonirrigated areas are in the North Central States and the fog-belt coastal areas of California.

Many of the problems in irrigating sugar beets are like the problems farmers meet when they irrigate other crops, but some are different.

Sugar beets grow in many climates, but they are irrigated mostly in the drier regions west of 100° west longitude.

Irrigation practices were developed immediately after the first successful beet sugar factory in the United States was established at Alvarado, Calif., in 1870. Early research workers in Utah, Nebraska, and elsewhere observed that beets could be grown with 15 to 30 inches of irrigation water, but that small, frequent irrigations were better than infrequent, heavy ones. F. S. Harris, director of the Utah Agricultural Experiment Station, made an extensive study about 1917 relative to the amount of irrigation water and frequency best suited to sugar beets. He obtained maximum yields with ten 1-inch irrigations for the season.

It is not possible to give a single satisfactory irrigation requirement for sugar beets for all areas, however, because conditions differ so much. The amount of water may vary considerably from what is usually thought of as the irrigation requirement for the crop. The actual use of irrigation water under any system may represent local practice only and may be economical or wasteful. Under the usual conditions, the use of water should approach the requirement for the maximum economic yield.

That amount for sugar beets may be modified by the method of irrigation and the depth of the water table in the soil profile—in addition to conditions of topography, texture of the soil, the climate, and perhaps others.

When the water table is 3 to 4.5 feet below the soil surface, sugar beets draw heavily on the ground water and produce creditable yields when the water is largely from that source. In general, however, attempts to restrict the plants in their normal use of water have meant uneconomical yields.

Both the consumptive use and irrigation requirement of sugar beets increase in most areas in June, remain relatively high and uniform in July and August, and drop perceptibly in September.

The monthly consumptive use and irrigation requirement, respectively, were calculated near Logan, Utah, by means of the Blaney-Criddle formula as follows: June, 4.57 and 6.00 inches; July, 5.27 and 7.83 inches; August, 4.80 and 6.86 inches; September, 3.63 and 4.06 inches.

That also would be the typical pattern in many areas where the beets are planted in April and harvested in October. It would be quite different in the Imperial Valley of southern California, where beets are planted in August and harvested the following June. Sugar beets in Montana reach a maximum water use by July 15 and maintain that maximum of approximately 0.22 inch a day until September 15.

The following figures indicate how climate influences consumptive use and irrigation requirement, respectively. They pertain to June–September, inclusive, and were calculated by the Blaney-Criddle formula (see page 343): Sacramento, Calif., 18.95 and 30.67 inches; Fort Collins, Colo., 17.50 and 19.50; Burley, Idaho, 18.18 and 26.78; Missoula, Mont., 17.04 and 20.39; Tucumcari, N. Mex., 19.85 and 22.37; Prosser, Wash., 18.85 and 29.17; Cheyenne, Wyo., 16.85 and 17.49.

The transpiration ratio of sugar beets is less than half that of alfalfa and approximately two-thirds that of potatoes. The sugar beet is therefore a relatively efficient user of irrigation water, as far as the production of dry matter is concerned.

The seasonal consumptive use of sugar beets is slightly more than that of potatoes, which has a transpiration ratio 50 percent greater than beets. That is due to the longer growing season of sugar beets. While the seasonal consumptive use of the sugar beet crop over most of the irrigated areas varies from 20 to 30 inches of water, the total irrigation requirement varies from 30 to 60 inches a season. The irrigation season is 80 days in areas of short seasons and is 150 days in places where the seasons are more favorable.

The total amount of irrigation water required to produce a crop of beets depends on the length of the growing season and the pattern of summer precipitation. Actually, it varies from 30 to 60 inches of water in localities where the crop depends largely on irrigation water. The number of irrigations varies from 5 to 12 over most of the area, but may be as high as 20 in the Imperial Valley of California.

The amount of water removed from the soil by sugar beets in transpiration and evaporation from the surrounding soil generally varies from 0.05 to 0.10 inch a day in June to 0.2 to 0.3 inch a day in August. The June loss in some places may be nearly as high as that indicated for August.

The length of the growing season and the distribution of rainfall during the growing season are of practical importance in determining the amount of water needed to grow sugar beets. In parts of California and Washington the growing season is 7 to 8 months; in many intermountain areas the time from planting to harvest is not more than 5 months. At Sacramento, the 4 months' rainfall, June–September, is 0.53 inch. At Scottsbluff, Nebr., where sugar beets also are grown under irrigation, the rainfall during the same period is 7.08 inches. The irrigation interval and total irrigation requirement are obviously quite different from area to area, where growing season and summer precipitation are so variable.

The rooting habits of the beet plant restrict the irrigation practices that should be considered in its production. Under favorable soil conditions, mature sugar beet roots may reach a depth of 4 feet or even 5 feet, but the plant gets about 65 percent of its moisture from the first foot and 20 percent from the second foot of soil, if moisture is available in those zones. As little as 5 percent of the water used by the plant comes from below the 3-foot depth, if moisture is available above that depth. Some research workers believe there is no need to be concerned with more than the upper 2 feet of surface soil during an irrigation. The greater the soil moisture reservoir, however, the less frequent need the irrigations be and the easier it is to irrigate efficiently.

The method of irrigation is an important point in the total amount of water needed for sugar beets.

Experimentally it has been shown that in order to maintain a silt loam soil under low soil moisture tension (moist) during the growth of sugar beets, about 50 percent more irrigation water is required under furrow irrigation than under sprinkler irrigation. The difference derives from greater efficiency in application, shallower percolation, and smaller losses in surface runoff when irrigation is done by sprinklers. The advantage becomes less as the depth of soil to be moistened at each irrigation increases, until it is practically eliminated when this depth approaches 3 feet.

Sprinkler irrigation has a special advantage over furrow irrigation immediately before planting and emergence and before and immediately after thinning the beets. The advantage is less as the roots penetrate to greater depths. But the efficient application of water by sprinkling should not be construed as a recommendation for the sprinkling of sugar beets. Many factors favor furrow methods. Sprinkling can be used in the growing of sugar beets, but furrow methods were used on more than 90 percent of the sugar beet acreage in 1955. Unless otherwise indicated, furrow irrigation is the method I refer to in this chapter.

Because the length of the growing season is probably the first limitation on the yield, the crop should be irrigated before the soil gets so dry as to delay plant growth. Any delay in the rate of growth is equivalent to shortening the growing season.

Occasionally one must irrigate before the crop is planted if the soil moisture is inadequate for germination. That can be done by flooding or by means

of corrugations. Soil moisture often seems to be enough at planting but becomes depleted by surface evaporation to the extent that germination may be spotty. That hazard can be lowered by attaching corrugation shovels to the beet drill, so that furrows will be made 44 inches apart, or between alternate rows during planting. Ample water can thereby be applied to moisten the soil around the seed, so that germination will be assured even in adverse periods.

Fields on which sugar beets are to be grown should be plowed in fall. An excellent seedbed can then be prepared by harrowing and leveling in the spring immediately before seeding. The practice usually insures enough soil moisture to germinate the seed and carry the seedlings to the thinning stage. Immediately after cultivation and thinning, the beets should be furrowed between each row and prepared for irrigation.

An exception to the practice of fall plowing occurs in the Plains States, where fall and winter wind erosion makes the practice hazardous. In those areas spring planting follows spring plowing immediately.

Proper irrigation requires the control and accurate distribution of the water. Ways of doing that are discussed on pages 258–278. A good way to irrigate sugar beets is to use field lateral ditches, with equalizing ditch and spiles, or to use field laterals direct to the furrows through spiles. Many growers use plastic siphon tubes or gated pipes in place of spiles.

Ways of determining how much water to apply at the various stages of plant growth are described on pages 341–381.

The beet plant is especially sensitive to unfavorable moisture conditions for 3 or 4 weeks after it emerges. During that time, the soil should be kept moist in the upper 12 inches, so that growth will be continuous and fast. If irrigation is necessary then, it should be light, so as to avoid leaching of soluble plant nutrients. As the plant becomes older and the root system is more firmly established, the plant becomes increasingly able to withstand moderate drought.

It is advisable to moisten the dry part of the soil at each irrigation. Depending on their texture and structure, soils can hold 1 to 3 inches of available water per foot of soil depth. A medium-textured loam soil will hold approximately 2 inches of available water per foot. If 75 percent of the available moisture is removed by transpiration from the upper 2 feet of such a soil, 3 inches of irrigation water are needed to moisten it fully. Assuming furrow irrigation to be about 60 percent efficient, the grower must provide 5 inches of water in order to obtain the 3 inches of available soil water per irrigation. If it is necessary to fill the soil reservoir to 3 feet on a similar soil, it will require 4.5 inches of available soil water or 7.5 inches of irrigation water at the head of the field. In terms of streamflow, it would require a stream of 1 cubic foot a second for 5 hours to provide 5 acre-inches of water an acre, and 7.5 hours for 7.5 acre-inches of water an acre.

If the crop needs an irrigation to keep it growing rapidly during the first 3 or 4 weeks following thinning, the application should be sufficient to moisten only the first foot of soil. Later irrigations should be enough to moisten the dry soil to 2 feet, and by the last of July to 3 feet. That will require 2 inches of water per irrigation for the early applications and 3 to 4 inches per irrigation later in the season to recharge the dry soil with available water. In order to limit water application to these small amounts and yet obtain uniform distribution by furrow methods, excellent control is necessary. The ideal is to moisten the dry soil with as little loss of water by deep percolation as possible.

Irrigation as a means of controlling or limiting the detrimental influence of soil salinity has a limited application but may be important in places where salinity is already a problem. The accumulation of excess soluble salts in

soils is generally a result of poor drainage. Therefore if excess salt is to be lessened or eliminated, adequate drainage must be provided. Once the sugar beet is established, it is moderately salt tolerant. Attempts are being made therefore to grow sugar beets on soils too salty for more sensitive crops. Winter flooding or preemergence irrigation can help materially in obtaining a stand of beets and in increasing the yield where moderate salinity exists. Overirrigation or winter flooding should not be practiced, however, unless drainage is good. When irrigation water of good quality is available and undersurface drainage also is good, one can get good yields on many soils now considered unsuited to sugar beets.

The shape and position of the seedbed in relation to the irrigation furrow may be highly important on saline soils. The seed should be planted above the water line and 3 or 4 inches to the side of the furrow on a sloping bed. Such an arrangement will allow satisfactory germination and establishment of young plants. Heavy concentration of soluble salts may accumulate on the high point of the bed several inches from the germinating seeds and young plants. After the plants are established, the permanent furrows can be relocated 10 or 11 inches from each beet row.

Timeliness of irrigation and the number of irrigations may influence yields. The number of irrigations and amounts of water previously thought necessary to produce a satisfactory crop can be reduced by timeliness of application.

Large yields are not enough. The percentage of sucrose and the purity of juices in the root also are important. Those points of quality are modified by available soil nitrogen, which is controlled to a considerable extent by irrigation practice. On a given soil, 15 inches of irrigation water may produce beets having 16 percent sucrose and 89 percent purity, while 28 inches of water may produce beets showing 17.5 percent sucrose and 92 percent purity.

Since both yield and quality of sugar beets are important and since both are modified by irrigation practice, one has to know the characteristics of the soil relative to moisture retention and available nitrogen as well as the irrigation requirement of the plant.

The quantity of available soil nitrogen is closely related to desirable irrigation practice. The yield of beets may be seriously depressed by too much irrigation water and by too little water. Under sprinkler irrigation, it may be impossible to increase the yield by nitrogen fertilization, but on the same soil under furrow irrigation 80 pounds of nitrogen may increase yields by 3 to 4 tons an acre. That results from the fact that under furrow irrigation available soil nitrogen is frequently lost by deep percolation. That is not so likely to happen under sprinkler irrigation. On a soil of moderate nitrogen availability, using sprinkler irrigation, it may be possible to obtain a yield of 15 tons of beets with 17 inches of water, 20 tons with 24 inches, and only 19 tons with 37 inches of water. That means that for those conditions, 17 inches of water did not provide an environment most conducive to beet growth; 37 inches of water was too much, perhaps because the excessive water had leached part of the available nitrogen beyond the reach of plants and caused a deficiency of nitrogen.

On a given soil, the concentration of nitrate nitrogen in the sugar-beet petiole may be less than 1,000 parts per million under furrow irrigation and more than 4,000 parts per million under sprinkler irrigation where the same total amount of water was applied under each method. With furrow irrigation, using 15 inches of water, 2,000 parts per million of nitrate nitrogen may be present in beet petioles at harvesttime, but less than 1,000 parts per million where 38 inches of water are used. But one should remember that the nutritional status of beets is not a matter only of amount of irrigation water. The amount of available soil nitrogen or fertilizer nitrogen tem-

pers the influence of irrigation water.

Limited experimental study indicates that the concentration of phosphorus in beet leaves and petioles is often increased by the frequency and quantity of irrigation, while the concentration of potassium is lowered. An increase in available soil phosphorus tends to depress the uptake of potassium. Thus the lower concentration of potassium as irrigation frequency is increased may be an indirect effect of increasing the uptake of phosphorus. Frequently, large amounts of available soil nitrogen decrease the concentration of phosphorus in the soil. I mentioned before that excess irrigation water may limit nitrogen uptake. Thus irrigation can be manipulated to favor or hinder the uptake of various nutrients.

The best nutritional condition of sugar-beet plants will be had by keeping the soil moist without excessive loss of water by deep percolation. Because the plants are not deep rooted, well controlled, light, and relatively frequent irrigations are suggested. As it is not possible to avoid some water losses under furrow irrigation, sufficient nitrogen fertilizer must be added to compensate for limited leaching losses while irrigating the crop to keep it growing rapidly.

The irrigation program for sugar beets sometimes starts before the seeds are planted. More frequently it starts after thinning and continues up to 2 weeks before harvest. The frequent use of a soil-moisture probe or soil auger will help to determine the depth of penetration of moisture. Continuous, rapid growth of the plants can be assured if irrigation water is applied when 40 to 80 percent of the available soil water has been removed from the root zone. That represents a soil-moisture tension range of about 1 to 4 atmospheres.

Because the rooting habits of sugar beets are known, moisture-measuring instruments make it possible to work out a satisfactory irrigation regime for the crop on any soil or in any climate in a few years of observation.

Each field of sugar beets presents its own problems as to length of run, size of stream, frequency of irrigation, and the time allowed for proper penetration, but the total requirement varies from 24 to 35 inches and (in seasons longer than the average) up to 60 inches of irrigation water annually.

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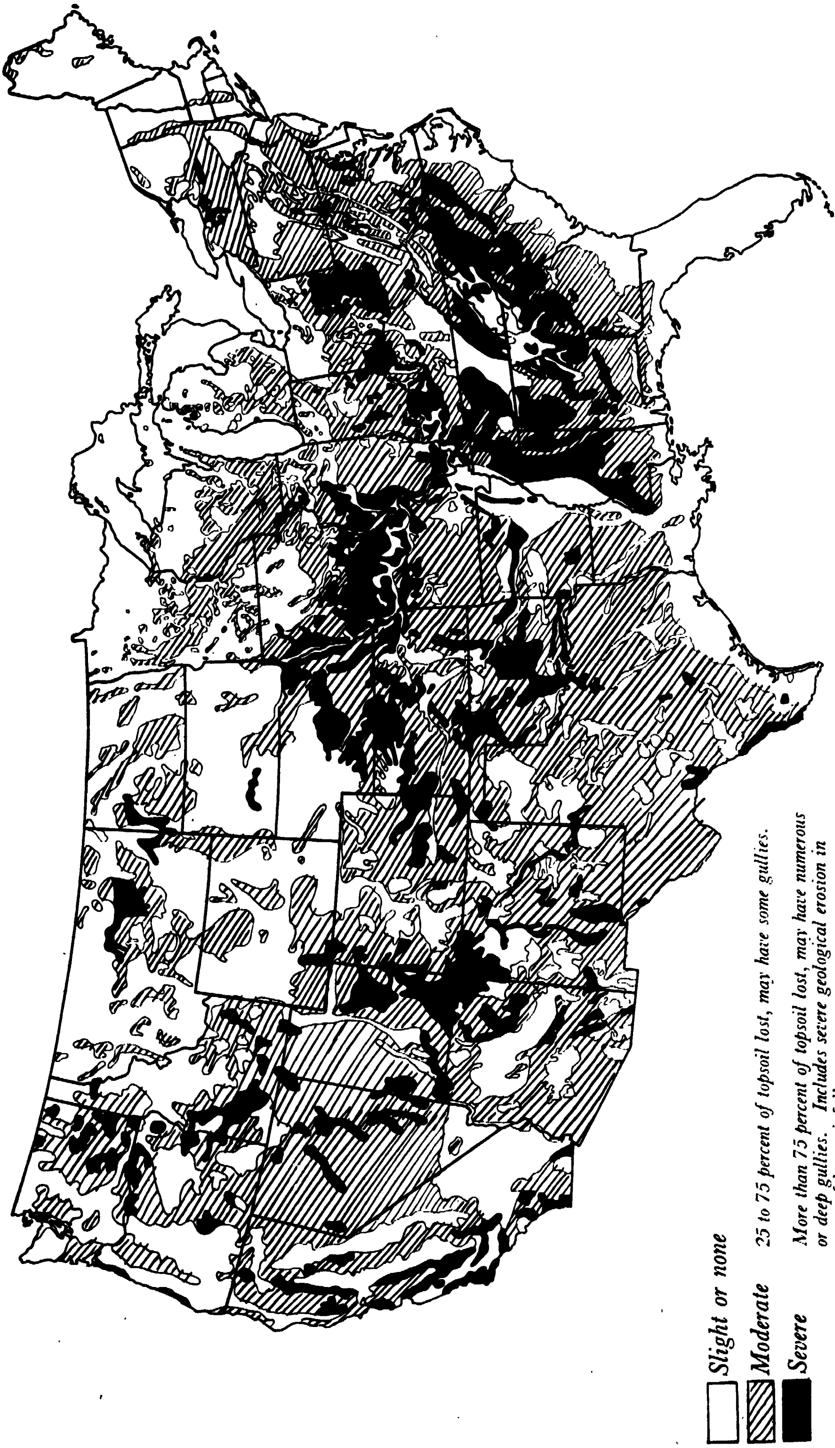
We think of our land and water and human resources not as static and sterile possessions but as lifegiving assets to be directed by wise provision for future days. We seek to use our natural resources not as a thing apart but as something that is interwoven with industry, labor, finance, taxation, agriculture, homes, recreation, good citizenship. The results of this interweaving will have a greater influence on the future American standard of living than all the rest of our economics put together.—FRANKLIN D. ROOSEVELT

So far as the world's food is concerned, all peoples must learn together to make proper use of the earth on which we live. Hovering even now over our shoulders is a specter as sinister as the atomic bomb because it could depopulate the earth and destroy our cities. This creeping terror is the wastage of the world's natural resources and particularly the criminal exploitation of the soil. What will it profit us to achieve the H-bomb and survive that tragedy or triumph if the generations that succeed us must starve in a world, because of our misuse, grown barren as the mountains of the moon?—DWIGHT D. EISENHOWER

Generalized Soil Erosion



Our Ranges and Pastures

Farming Where Rainfall Is 8–20 Inches a Year

F. L. Duley and J. J. Coyle

Dryland farming no longer means simply farming in a region of low rainfall. Rather, it has come to refer to a fairly well established system of managing crops and soils that is adapted to semiarid or dry climates.

Such a climate exists in various parts of the world, including parts of all the Western States, notably the Great Plains, the Great Basin, the Pacific Northwest, and the Central Valley in California.

The total precipitation in the dry-farming areas generally is low, about 20 inches down to 8 inches annually.

Scant rainfall, though, is only one aspect. The average temperature in the Northern States is much lower than in the Southwestern States. A given amount of precipitation therefore is much more effective in the North than in the South. The distribution of the precipitation through the year also is important. The limited precipitation in parts of the Pacific Northwest comes mainly in winter, when evaporation is low. So the rain penetrates deeper into the soil and subsoil than does the much higher rainfall of the Central Plains, where the moisture comes chiefly in summer. A rain of one-half inch on a hot, dry day may lose so much of the water by evaporation that only a small fraction is available to the plant. During cool weather a rain of one-half inch may penetrate the soil to the extent that much of it may be used eventually by a crop.

Wind erosion of the soil is common in most dry-farming regions, particularly in sandy areas. In many places an occasional torrential rain or a sudden heavy shower may cause considerable erosion.

GREAT PROGRESS has been made toward producing a great share of the Nation's food in the West, a part of which the early explorers called the Great American Desert. Livestock and small grains are the food products that can be grown to best advantage. Research has had a great effect on the progress of all limited-rainfall regions. The mechanization of farm operations has altered labor requirements and has changed the cost of production in regions where an extensive agriculture is practiced.

As the Great Plains were settled, largely during the last quarter of the 19th century, farmers drove their covered wagons westward from the humid areas of the Eastern States to those low-rainfall regions. They brought with them the methods of a humid agriculture. They also brought the seed for crops that had been found suitable for humid conditions. They soon learned that the types and varieties of

crops they had used back east would not withstand the climate of the Plains: Corn was not successful in most years. The soft wheats of the East would not produce satisfactory yields in the Plains.

New methods were developed only with the coming of certain Europeans, like the German-Russians, who settled in central and western Kansas. They brought from the regions around the Black Sea varieties of hard red winter wheats that had been grown under conditions like those of the Great Plains. Since then great improvement has been made in varieties and in the methods of managing soils and crops, and greater agricultural stability has come to all dry-farming localities.

The improvement in methods came from two main directions: The hard-earned experience of farmers in the new and demanding environment and the work of experiment stations.

THE EXPERIMENT STATIONS for studying dryland problems were authorized by the Congress in 1905. Within the next decade about 25 stations were established in the dry-farming areas.

Some stations gave attention to livestock. Some studied horticulture, landscape gardening, and forestry so as to improve living conditions on the Plains. But their work was devoted mainly to problems of soils and crops—testing and comparing methods of production, conserving soil moisture, and, much later, conserving the soil itself.

FAILURE TO RECOGNIZE the capability of the land brought about a great number of failures in the dryland areas.

Many of the critical problems there arose because of plowing up grassland that is unsuited for cropping in places of limited rainfall. Particularly in the southern part are the soils hazardous—very sandy or shallow. An estimated 7 to 8 million acres of that kind were cultivated in the Southern Great Plains in 1954. Even moderately sandy and moderately deep soils in the southern dryland regions are hard to protect against wind damage if they are placed under cultivation. It is advisable to cultivate them only occasionally. Grass should cover the land at least half the time.

Steepness of slope adds to the complexity of the erosion problem. Cultivated lands on 2-percent to 5-percent slopes in the 17-inch rainfall belt of the Southern Plains tend to be damaged 2½ times as fast as similar land that is nearly level. When rain totals 20 inches, the rate of erosion becomes about 16 times faster.

The slope of a piece of land should therefore be given full consideration in deciding whether it is suitable for long-time cultivation.

LIVESTOCK MEN were the first settlers in the Plains and other dryland areas of the United States. Up to that time the Indians had obtained much of their food from the great herds of buffalo. Cattle replaced the buffalo, and the cattlemen virtually took over the Plains as a grazing region.

As settlements increased and towns grew, the demand for farmland increased. The cattlemen were thus gradually pushed back until all the land that could be plowed easily had been broken. The open range disappeared and barbed wire enclosed the plowed fields and pastures. Mostly only rough land was left for grazing, which farmers used for small herds, which got some feed from crops grown on the plowed land.

This livestock system has come to be one of the stabilizing types of dryland farming. The man who lives on the land and farms on a year-round basis usually gets along better and is more sure of a good living if he has some livestock.

He can then work out his cropping system so as to make use of land for grazing and also produce grain and rough feed for winter. His main precaution is to adjust the number of livestock to the feed and pasture he will probably have in unfavorable years.

He then will be able to build up some reserve supply of feed for the poor years, or he may have some for sale in good years.

The crops grown for feeding vary in different sections of the dry-farming area. Grain sorghums, sudan grass, or some type of sorghum for hay may be used in the southern part of the Plains to supplement native pasture. Some legumes, like cowpeas for feed, and pinto beans may be grown if climate is favorable. In many places wheat may be used for pasture at certain times if overgrazing and pasturing too late are avoided.

In the central and northern parts, some other crops may be used to supplement the pasture. Some corn may be produced, but sorghums are less well adapted than farther south. Barley and oats also are feed crops. Rye may be used for pasture and in some localities vetch may be seeded with it.

Throughout the dryland country, cattle seem to be the type of livestock best adapted to the climate and the type of feed available. They make good use of native grasses and can be wintered on rough feed and native grass hay.

In extensive areas in many parts of the Plains cattle raising is still the main industry. Rangelands may be concentrated in a large block of country with only limited areas of farmland. What farmland there is may be mostly irrigated. Examples of these extensive range areas are in the Sandhills of Nebraska and the short-grass country in eastern Wyoming, Montana, and several other Western States.

In some areas sheep have been grazed in mountains and foothills. Texas, Wyoming, Montana, California, New Mexico, Utah, and Idaho have produced thousands of sheep as range animals. It is a type of livestock production for low-rainfall regions, but is not classed as typical dryland farming, since in these areas it is chiefly a range type of livestock production and involves a minimum of crop production to support it.

Soil erosion by wind and water has come to be a big problem in nearly all dry-farming areas. Special precautions need to be taken against erosion wherever the sod has been broken and cultivated crops grown. On steep slopes an occasional heavy shower or the water from melting snow may cause severe erosion if the land is in a condition to wash.

On level land, as well as on rolling or hilly land, wind erosion does extensive damage to crops and soils. In practically all dry-farming regions the control of wind erosion is one of the most important points in any system of farming. Wind erosion may not be severe every year, but it is always a threat and can occur almost any year if the principles of control have been neglected.

Sandy soils are more subject to wind erosion, and on them it is harder to control. Fine-textured soils may also suffer from wind erosion, and during long droughts they may suffer from soil drifting.

Some effective yet simple methods have been developed to hold down wind erosion. Some of the more important principles of control are:

Keep the soil covered with a growing crop as much of the time as possible.

When land is not in a growing crop, keep the residue from the previous crop on it by the use of stubble mulch, in which the land is tilled with an implement that pulverizes the soil without inverting it or burying the residue.

Use strip cropping—alternate strips of growing crop and stubble or stubble-mulch fallow.

Make use of cloddy fallow.

Use tree shelterbelts or strips of tall growing crops to protect adjoining land.

Use emergency methods of tillage when soil starts to drift.

The equipment needed for use against wind erosion is discussed under methods of preparing the seedbed for wheat.

Steps to avoid wind erosion should

be taken at least a year before the time that erosion is most likely to occur. If an attempt is made to control the erosion by shelterbelts, the trees may have to be planted several years before they can be expected to have much effect.

Highly effective in many areas is the stubble-mulch method. It involves the use of stubble, straw, stalks, or other form of residue to reduce the velocity of the wind at ground level and thus reduce its ability to move soil. A common form of stubble mulch is wheat stubble and straw left after the combine. It must be left on the surface during the preparation of the seedbed for the next crop. Row crops that leave a dense stubble may also offer effective protection.

Sudan or sorghum, even though much of the plant is removed for hay or feed, may still leave a dense stubble in the row. If it is cut 6 to 12 inches high, depending on the density, the field may be reasonably well protected. Such stubble should be left upright until the next crop is planted, if possible. Sometimes it is feasible to drill small grain or grass mixtures in the stubble without previous cultivation if there are no weeds. If that can be done, the old stubble may afford effective protection against wind erosion while the new grass crop is getting started. Cornstalks or sparse stubble usually do not give good protection.

A third method, that of using strip crops to control wind erosion, has been widely used in some sections. Alternating strips of wheat and fallow may be 5 to 10 rods wide or even wider. Sometimes they are at right angles to the most destructive winds. Sometimes the strips are on the contour to get the greatest protection against runoff and erosion during a heavy rain. If the fallow strip is handled by the stubble-mulch method, almost complete protection against wind erosion usually can be achieved.

In this system one strip would be in growing wheat, which was seeded on mulched land for protection against soil blowing. The adjoining strips would be receiving the fallow treatment, in which the land is subtilled with equipment that leaves the residue on the surface. After the wheat is harvested, the stubble and straw protect that strip, and the fallowed strip is seeded to wheat. All the land is thus protected at all times.

Cloddy fallow may be used with any type of fallowing; if the surface is left largely covered with clods that cannot be moved by the wind they will protect the fine material from blowing. Fine-textured soils form rather stable clods that protect the soil. Sandy soils do not form stable clods; even if the soil is worked when moist, the clods weather down quickly. The effectiveness of the method therefore depends on the kind of soil.

The use of tree shelterbelts received a great stimulus during the decade 1933–1942. Millions of trees were planted in the Great Plains with the idea that they would greatly affect wind movements and do much toward controlling wind erosion. Narrow belts have been placed at intervals of 20 to 40 rods in some sandy areas.

After the trees reach considerable height under such conditions, they are quite effective in reducing wind damage to the soil or crops.

The use of shelterbelts seems to have about reached its peak, for several reasons: They take considerable space away from the cultivated acreage on the farm; their esthetic value is great, but their economic value may be questionable; we have agronomic methods for reducing wind erosion.

The use of emergency tillage methods is usually brought into use when more effective methods have been neglected. If a cultivated field has no growing crop or residue on it, wind erosion may start. Roughening the surface or a part of it may then stop soil movement over the entire area. Any shovel-type tillage implement, like a plow, lister, or shovel cultivator, will throw up clods or chunks of soil, which will tend to stop soil movement. One or two lister furrows spaced 2 or 3 rods apart

across the field may hold the soil or a wheat field from drifting for a while.

It may be necessary to run more furrows between the first ones if drifting starts again. Disk tools may be used to stop wind erosion on tilled land temporarily, but since disk implements tend to pulverize the soil and do not throw up clods, they are less effective than shovel-type tools.

If land is kept covered with stubble mulch, the emergency methods will seldom be needed. Emergency methods are sometimes necessary on a large scale if widespread drought has reduced the amount of mulch protection that can be provided. Some States have laws requiring farmers to use emergency methods when needed.

WATER EROSION is a more serious problem in the dryland farming area than is generally thought. In the eastern part, a rainfall intensity of 3 inches an hour for 30 minutes can be expected to occur about once in 5 years. The comparable figure farther west is about 1 inch. Only permeable soils or soils protected with residue can absorb rains of that intensity.

The resulting runoff creates a water erosion problem on the more sloping land and on nearly level land if the slopes are long, because the water accumulates on the lower part of the slopes. A stubble mulch effectively controls water erosion, as well as wind erosion. The litter maintained on or in the surface breaks the force of the falling raindrop, reduces the speed with which water moves across the land, and maintains a favorable condition for intake of water at the soil surface. If slopes are so long or steep that residues will not control erosion, mechanical measures, such as terraces and contouring, are needed.

Terraces generally are considered applicable on slopes steeper than about 1 percent, on which even small concentrations of flowing water attain erosive velocities. Terraces intercept the runoff before it reaches damaging proportions.

On long slopes of less than 1 percent, one or more diversions may be needed to reduce the length to one on which erosion can be controlled by vegetative measures.

The diversions may be several hundred feet apart. Even on the gentle slopes some farmers prefer a regular terrace system with closer spacing because they help conserve water. Planting and cultivating row crops on the contour has noticeable benefits in some years and is especially important on terraced land. Contour drilling of wheat is especially beneficial if deep-furrow drills are used.

THE TERM "crop rotation" is less aptly applied in dry-farming areas than elsewhere: There are fewer crops from which to choose and few legumes that can be generally used to maintain the nitrogen supply in the soil. It is therefore not so important that any particular sequence of crops be followed. One of the main considerations is to arrange the sequence with a view to the possibility of a moisture supply for the oncoming crop. For example, corn (in areas where it is adapted) usually leaves the soil with a better supply of moisture than does small grain. Wheat usually exhausts the available soil moisture almost entirely by harvest-time. Consequently some time should elapse before another crop is seeded. Early preparation of the seedbed after wheat is essential if another seeding of wheat is to follow.

Wheat may often be seeded on cornland from which the crop is removed for fodder or silage. Or it may be drilled between wide-spaced corn rows.

Another reason for not using the term "rotation" so much is the possibility of crop failure. Because of the wide fluctuations in annual rainfall, nearly all dryland areas experience some crop failures or near failures, which may break the sequence of a rotation. Then the farmer has to put in the crop that has the best chance for success under the conditions of soil moisture and weather at the time.

Some examples of types of cropping systems that might be adapted in different parts of the dryland farming areas of the United States are: Corn, wheat, wheat; corn, wheat, fallow, wheat; corn in wide rows, wheat, wheat on early worked land; wheat, fallow; wheat, sorghum, fallow; corn removed for silage, wheat; corn, barley, fallow, wheat; wheat, peas for canning; wheat, grass several years, sorghum, small grain; kafir, cowpeas, milo (Southern Plains).

The type of cropping system used on a given farm has evolved on the basis of the type of farming a man wanted to carry out. Several rather distinct types of dryland farms exist.

The first is the general farm that has considerable livestock. This type usually occurs in localities in which a good supply of range or pastureland is available to supply summer grazing. Enough grain and roughage should be produced to carry the livestock through the winter. Practically all crops produced are fed on the farm. Nearly all the income is obtained from the sale of livestock and livestock products. Some livestock and a limited acreage for feed crops may mean a more stable system and a more steady income than a one-crop wheat system. In many areas the total longtime income may be higher with a wheat system, but that, it must be admitted, will mean some total failures. The farmer must decide whether he can stand the financial strain in order to realize more income in the long run.

Another type of mixed farming is the cash-grain farm, in which the returns are from the sale of grain, seed, or hay.

The wheat farm derives practically all its income from the sale of wheat. The farmer lives on the land and devotes his time chiefly to this one enterprise.

The "suitcase" farmer is the absentee wheat grower. He may have a profession or business in a city and occasionally visit the farm or employ someone to do the farm work. He does not become part of the farm community. He may not see the wind erosion in the spring; maybe he does nothing to help control erosion during that season.

Some farmers try to adjust their plantings on the basis of the moisture present in the soil at seeding time. The practice returns a higher total income over a period, although there may be considerable variability from year to year.

Suppose a man started out on the basis of a wheat-fallow system. If good rains should follow harvest, he might get moisture into the soil to a depth of 2 feet or more. Then he might decide not to fallow the land the following year but to put it back to wheat for another year. Likewise, if he held wheatland over with the idea of fallowing for another wheat crop, but found the soil well filled with moisture by spring, he would have the choice of several crops. He could hold it over for wheat, but would produce no crop that year. Instead he might plant the land to corn, sorghum, potatoes, or some other crop and thus make use of the soil moisture as soon as possible after it had been stored.

This idea of farming according to the moisture supply offers a basic principle for the dryland farmer. If he would plant a crop in season every time he has an adequate supply of soil moisture and leave the seed in the bag when he does not have the moisture, he would put his farming on a more realistic basis. He would be taking less of a chance with the possibility of rain after the crop is planted. If the idea were adopted, a tile spade or a soil auger should become standard equipment on a dryland farm. Either of those tools permits a farmer to determine quickly the depth to which the moisture has been stored in the soil.

Available soil moisture is one of the main concerns in dryland farming. The rainfall during the time a crop is on the land seldom is enough to produce a good crop. It is necessary therefore to have some reserve moisture

stored in the soil before the crop is planted.

Research workers of the Kansas Agricultural Experiment Station at Hays found that when wheat was seeded in dry soil with no available moisture stored in the subsoil the average yield of wheat was 4.9 bushels an acre; when the soil was wet 1 foot deep at seeding time, 8.7 bushels; wet 2 feet deep, 15.2 bushels; and when wet 3 feet deep or more, 26.5 bushels an acre. The uneven distribution of rainfall and the frequent occurrence of extended dry periods has led to the practice of fallowing. This means keeping the land free of a crop or weeds for a period of time so that moisture and nitrates may be accumulated in the soil for use by the next crop.

A year of wheat followed by a year of fallow has come to be a common practice in the wheat territory. A wheat crop is harvested in the central Great Plains in July. Unless the field becomes weedy the land is allowed to lie without treatment until the following spring, when tillage operations for fallow begin. The land to be fallowed would be one-wayed or plowed about the first of May or about the time weeds or volunteer wheat start. The land is then worked often enough to keep down weeds. Many men work the land oftener than necessary to keep down weeds, but do it to break the crust on the surface of plowed land, to reduce runoff during the next rain, and to avoid wind erosion on smooth, crusted soil.

Work at numerous dryland experiment stations has shown that deep working of the soil has not perceptibly mitigated the effect of drought. It has not increased yields of crops enough to be profitable, no matter what method has been used to deepen the cultivated layer of soil. Despite the proof furnished by 60 years of experiments, which have failed to show any consistent profit from deep tillage or tilling into the subsoil, interest in the practice waxes and wanes periodically. Perhaps deeper tillage may be of some value in connection with the deeper placement of fertilizers, but that point has had little study in regions of limited rainfall.

Fertilizers have been used very little in most of our dry-farming areas, as those soils are reasonably well supplied with the mineral elements plants need. In some places the addition of phosphorus has given favorable results. Enough nitrogen usually is present to allow crops to make use of the available moisture—especially if a crop follows fallow.

Fallowing not only allows the soil to store water, but it accumulates nitrates at the same time. The use of nitrogen fertilizer on fallowed land has given little return in most places and usually has been considered impractical. On some soils, particularly the sandier types, good results from nitrogen fertilizers have been obtained, even on fallowed land. Increases in yield of grain, straw, or protein content have been obtained under many conditions.

As to the future: As the fertility of dryland soils is gradually reduced through cropping, greater returns from the use of fertilizers can be expected. After a half century of farming, nitrogen fertilizers may begin to show greater returns on many dryland soils. If one crop follows another without an intervening fallow, added nitrogen in the form of fertilizer may offset somewhat the effect of no fallow, especially if the moisture is reasonably adequate. Chemical analyses of soils in various parts of the dryland region have shown that they have lost 25 to 40 percent of their total nitrogen since the land was put under cultivation.

Since many of the soils have been farmed for only 30 to 50 years, the loss can be considered serious. The use of nitrogen fertilizer would appear to be only a matter of time. The need for phosphorus or other mineral elements will be ascertained for various localities as the land continues to be farmed.

The use of barnyard manure has given only slight returns. Likewise

green manure has not been very effective in improving the growth of the following crop. The benefits from these treatments may increase after the land has been farmed for a longer time, and further experiments determine the most effective methods of using them.

Some farmers burn straw and stubble before preparing the seedbed for the next crop. Often they have found that the yields were as high as from land where the straw was not burned. Since tillage was easier after burning, they have asked whether the practice is sound. The explanation of the good yields following the burning of stubble involves several points. In the first place, burning all the trash on the field makes possible a good, smooth job of plowing.

The rate of nitrate accumulation may be increased for a time after the straw is burned. The soil micro-organisms which cause straw to decay use some nitrate present in the soil for their own growth; consequently in the burned area this reaction does not take place and more nitrate may be stored for the immediate use of the wheat crop. If the straw is burned every year for a few years, however, the advantage in improved yields at the start gradually disappears. The land to which straw was returned may then give the higher yields.

The great advantages in returning straw, instead of burning it, is that the straw increases the capacity of the soil to absorb water and protects it against wind erosion. The nitrogen returned with straw amounts to about 10 pounds a ton of straw.

THE EQUIPMENT for dryland farming used by the early settlers was what they took along with them. The tough grass sod was first broken with a sod plow, or prairie breaker, which had a long moldboard, or steel bar, for inverting the furrow slice.

In later years came the stubble plow, which had a much shorter moldboard. It turned the furrow slice and did much pulverizing of the soil.

Much of the early research on the dryland experimental farms was concerned with the time and depth of moldboard plowing for various crops. Plowing was a good way to start preparation of a seed bed, but later people realized that it had some shortcomings. It permitted much erosion during heavy rains and exposed the soil to severe wind erosion.

Other types of tillage tools have been introduced since. One of the most widely used is the one-way diskplow. It stirs the soil, gives a minimum of trouble in operation, and land can be covered rapidly with it. The principal objections are that, being a disk implement, it tends to pulverize the soil too finely and tends to bury the crop residue too completely. It may be used for the first operation to kill weeds and volunteer plants, but if used a second time or more it may bury most of the residue and lead to wind erosion.

A more appropriate implement for the second and later operations is the subtiller, usually a V-sweep-type machine that has come into use for stubble-mulch farming. By the careful use of subtillers, enough residue may be preserved from one crop to hold the soil until the next crop is started to control wind and water erosion. With this stubble-mulch system, of course, other useful methods should be used—practical cropping systems, stripcropping, cloddy fallow, and sometimes terracing.

The use of power machinery has helped the dryland farmer immeasurably. Tractors and large equipment enable him to do his tillage, seeding, and harvesting operations in less time and at the most advantageous time. Timely operations may be of importance not only for the crop but also in the control of insects and diseases.

RESEEDING dry-farming land to grass has been suggested as a way to treat the drylands that are not well adapted to cultivation.

A considerable amount of reseeding is done by farmers who need additional

pastureland to support their livestock program. But many farmers feel that they will realize a higher return from the land if it is in cultivated crops. Another reason why reseeding to grass is not done more widely is that it is hard to establish grass on cultivated land. Very dry weather may follow seeding, so that germination will be low and the chance for survival of the seedlings greatly reduced. Only about one-third as much land is seeded to grass in the 17 Western States as is seeded in the rest of the country.

The types of grass used in different parts of the dry-farming area vary with climatic conditions. The methods of seeding also vary widely. In order to conserve moisture and obtain protection against soil blowing, much of the grass seeding is being done through some sort of residue cover. In the Northern Plains it is common practice to drill grass seed into wheat stubble in late fall with no previous seedbed preparation. The seed is then in the ground ready to germinate and start growth with the first warm days of spring, when the soil very likely is moist enough.

In the Southern Plains some tillage of the seedbed may be given, but the seeding is best done with drills that have depth gages, so the seed will be planted deep enough to get moisture but not so deep that the seedlings cannot come through to produce a good stand. Seeding with some protective residue cover aids in holding moisture for germination and prevents the young plants from being blown out or from being cut off by blowing soil or sand particles.

The seeding program in dryland areas depends on a number of circumstances. The wheat acreage allotments may induce many men to put idle acres to grass. A change in the relative demand for wheat and cattle also may affect it. Any general trend toward mixed farming would encourage the seeding of more land to grass. Eventually we may have a better adjustment of cultivated crops to those lands well suited to their use. The rough lands, or those for other reasons not so well suited to cultivation, may gradually be put to the grasses best adapted to the locality.

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Management of Water on Western Rangelands

F. G. Renner and L. D. Love

Ever since they trailed the first herds across the "mile wide and inch deep" rivers of the Great Plains on the way to northern markets, western stockmen have been acutely aware of the importance of water.

A permanent stream meant a good location for a ranch headquarters, and nearby subirrigated meadows assured an ample supply of native hay. Flowing springs meant a daily supply of water for the livestock, and if the springs were well distributed the grass could be used more efficiently with less work by the owner. Even the underground water was important. If surface supplies were scanty or not dependable, the underground water that could be reached by shallow wells permitted

use of vast areas of new range that would otherwise lie unproductive.

Of all the waters, however, the stockman is most conscious of the rain. It is the source of his surface and underground supplies. It furnishes the life-giving moisture necessary for a grass crop. If the rains fail, the grass crop is short. If the drought persists for many months, the stockman has no alternatives but to seek greener pastures elsewhere, ship in costly feeds, or dispose of his livestock. That is especially so where ranges are depleted. Western stockmen, with one eye always cocked at the weather, have long realized how dependent their business is on water and have spent considerable sums to provide dependable supplies, to protect them, and, in times past, to fight for them.

Until fairly recently, attention to water problems on western ranges has been largely concerned with insuring adequate water for livestock. Most western ranches now have enough water for this purpose, although many additional watering facilities need to be developed to improve grazing distribution. The big task ahead is to increase the amount of water available for the production of grass. It is not even necessary to increase the rainfall, although that, too, has been tried. The same effect is reached in a variety of other ways, many of which progressive ranchers are practicing on hundreds of thousands of acres, frequently with startling results.

Measured by the condition of the range, forage production over the West as a whole is little more than half of what it could be. One inference to be drawn from this fact is that half of the water on western ranges is wasted—wasted in the production of useless vegetation, by excessive evaporation, and through runoff. If the preventable losses were to be eliminated and the increased water supplies efficiently used, forage production could be doubled. Of all the measures available for doing so, improved management offers the greatest possibilities.

The amount of vegetation on the ground throughout the grazing season has a major influence on how much of the water is put to productive use, how much of it evaporates, and how much escapes through runoff. Consequently the first consideration in any plan of management designed to make the most efficient use of the available water is to decide on the intensity of use.

The intensity should be such as to assure the maximum amount of vegetation on the ground at all times, consistent with high forage production and sustained livestock gains. The proper intensity of use will usually not only leave more vegetation on the ground but, by saving more water, will result also in higher forage yields and consequently more rapid livestock gains and a greater net return.

Many years of practical experience by ranchers indicate that "take-half-and-leave-half" is a good rule of thumb to follow on most ranges. Under some conditions, however, even that use is not light enough. A 7-year study of depleted ponderosa pine ranges showed that removal of 50 percent or more of the grass by cattle each year reduced the vegetation still further and gave a net return of only 74 cents an acre. In comparison, more moderate use that left from 60 to 65 percent of the vegetation on the ground improved the condition of the range and gave an average return of 1.35 dollars an acre.

Particular care should be taken to adjust the stocking rate in accordance with the current growth of forage. The reason is that the amount of forage produced on rangelands normally fluctuates greatly from year to year. Curly mesquite-buffalograss ranges near San Angelo, Tex., for example, produced 1,361 pounds of forage an acre in 1946, 980 pounds in 1947, and 327 pounds in 1948—less than one-fourth the production of 2 years earlier. With wide fluctuations in forage production the normal situation, stocking the range on the basis of average conditions wastes feed in the good years and brings disaster in the poor ones. The only way to

avoid that is to vary the stocking rate year by year, or during the year if necessary, in accordance with the actual forage production.

ONE WAY TO INCREASE the water available for grass is to make sure the rainfall is absorbed by the soil. Several factors influence the rate at which water penetrates the soil, as well as the amount it will hold. Normally, these include the depth of the soil, its porosity, and the condition of the surface.

The amount of cover left during and after grazing has a tremendous influence on both porosity and surface conditions, and hence on the amount of rainfall absorbed by the soil. If the range is kept closely grazed, the upper soil layers become compacted, the natural litter is broken up and dispersed, and there is little vegetation to break the force of the raindrops and prevent surface sealing. In those circumstances, most of the water runs off and little is retained to keep the existing plants growing vigorously, thus insuring an ample supply of forage for the livestock. On the other hand, if the range is maintained in good or excellent condition, with enough cover left at all times to prevent compaction and sealing of the surface, most of the rain is absorbed and continues to be available for plant growth.

Failure to maintain a good cover of vegetation on the land may lead to drought conditions, even when the rainfall is normal. The soils of deteriorated areas become drier and dry out more frequently than similar lands having good vegetation. It is a common experience to observe that summer rains penetrate but an inch or two on bare areas, while the soil is wet to several times that depth where there is a good plant cover. In contrast, soil temperatures are reduced from 10° to 40° under a cover of vegetation, evaporation losses are less, and the soil retains much of its moisture for days after less protected areas are dry. The abnormal loss of moisture under a reduced plant cover has a profound effect on the growth and survival of plants, changing grasslands to shrub deserts in some areas and invariably increasing the difficulties of revegetation.

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Observations of the effect of plant cover on the retention of moisture by the soil are supported by actual tests under a great variety of conditions. For example, a deep sand with an ample cover of little bluestem absorbed 92 percent of the moisture from a 2-inch rain, while the same kind of soil with practically no vegetation on it absorbed only 21 percent. Except on very shallow soils, the amount of cover was far more important than either soil texture or depth in affecting the quantity of water absorbed. A deep, fine-textured, permeable clay loam adequately protected by a dense cover of vegetation took in 97 percent of the water from a 2-inch storm—even more than the deep sand. The same kind of soil, grazed to the point where it supported only a sparse stand of annual weeds, absorbed only 10 percent of the water.

A STUDY in Colorado illustrates how livestock grazing increases runoff and erosion. Runoff and erosion caused by summer cloudburst storms have been measured, beginning in 1937, on six small plots in the ponderosa pine-bunchgrass type. The plots are located on a 17.5-percent slope with a north exposure at an elevation of 7,600 feet. Moderate grazing on this type of range results in the utilization of 30 to 40 percent of the annual herbage, but if grazing is heavy, utilization is 60 to 75 percent. Stubble height of the key species, Arizona fescue and mountain muhly, provides a reliable indicator of utilization.

An analysis of runoff from the untreated check plots for 16 years after 1937 showed that individual summer storms that produce measurable surface runoff occur on the average of 4 to 5 times a year; runoff occurring during the months of June through September results from individual rainstorms and responds to variations

in the composition of the grass stand as it is altered by grazing treatment.

In a period before the plots were subjected to the different intensities of grazing, the average runoff varied from 0.24 to 0.27 inch. The differences were not statistically significant, but they became significant soon after treatment, as average amounts of runoff began to reflect variations in grazing intensities. In 12 years the average runoff per season was 0.34 inch on the heavily grazed plots; 0.22 inch on those moderately grazed; and 0.11 inch on the ungrazed plots.

Grazing has also caused an increase in erosion, but not in direct proportion to the intensity of use. Before grazing by livestock, erosion occurred as the result of 4 separate storms in 3 summer seasons, and ranged from 111 pounds to 163 pounds an acre. Following the initiation of grazing treatment, 13 storms were big enough to produce erosion. Average annual depositions for seasons of occurrence were 134, 145, and 316 pounds an acre, respectively, on the ungrazed, moderately grazed, and heavily grazed plots. A significant increase in erosion has resulted from heavy grazing, while erosion from moderately grazed plots remained near normal.

The plot studies have been substantiated on a larger scale by water-absorption tests on 300-acre ponderosa pine-bunchgrass native ranges, where similar moderate and heavy utilization goals have been achieved since 1942. These tests, on soils like those of the plots, showed that the water-absorption rate of the moderately grazed native ranges was nearly twice (2.28 inches an hour) that of the heavily grazed ranges (1.18 inches an hour). Likewise, the amount of soil erosion occurring from each inch of surface runoff was nearly twice as much from heavily grazed ranges (263 pounds an acre) as from moderately grazed ranges (121 pounds an acre).

The results are significant. More and more western ranchers have come to recognize they have it in their own power to increase the amount of moisture available to their forage plants. By leaving more vegetation on the ground, they may double or triple the amount of moisture that enters the soil and actually increase the effective rainfall by that amount. The water that is saved helps to build up the range more rapidly and increases the forage supply in the process.

ANOTHER WAY in which stockmen have undertaken to increase water for grass production is to reduce its use by woody plants. Several species of sagebrush throughout the West, mesquite and juniper in the Southwest, numerous chaparral plants on California ranges, scrub oaks in Arkansas and Louisiana, and many others now infest one-quarter of the 950-million acre range area in the United States.

Those plants produce little or no forage and use water inefficiently. Many of the shrubs require 2 to 4 times more water to produce a pound of dry matter than do the perennial grasses. The amount of water needed to produce 740 pounds of dry matter of mesquite, 600 pounds of burroweed, or 1,200 pounds of fringed sagebrush, for example, would produce a ton of blue grama. Moreover, once some of the shrubs become established in normal grasslands, they have the effect of increasing the aridity of the area because they provide little protection against runoff and make it almost impossible for the grasses to become reestablished naturally. If the stands of these woody plants can be reduced. great quantities of water could be made available for a better use.

The present extent of such woody species throughout the grasslands is the result of a combination of conditions that adversely affected the grasses and favored the brush—chiefly overuse of the range, drought, and fire. Sometimes fire was not used judiciously to keep certain brush species under control. Sometimes repeated fires eventually eliminated the grasses and favored certain fire-resistant brush species. It is

probable, too, that the practice of stocking the range with a fixed number of animals year after year, without regard to drought or other periods of light production of forage, contributed to the increase of some of the woody species.

A variety of methods is being used to thin out or eliminate such plants and the extensive demand for such control has stimulated manufacturers to devise special machines for the purpose.

Bulldozers equipped with special cutting bars that sever the roots and lift large shrubs out of the ground have been used successfully with mesquite. Rolling cutters, consisting of heavy cylinders with attached blades, are used on many of the smaller shrubs. Some of the shallower rooted trees, such as junipers, can be upended by dragging them out with a heavy cable attached to a pair of tractors or bulldozers.

Mechanical flails and some types of farm machinery, such as corncutters, have been used on big sagebrush, but most of them are not sufficiently rugged to perform effectively. Heavy-duty mowers are effective on certain types of shrubs if there are few rocks in the soil and the terrain is relatively smooth. Heavy disk plows are the common equipment for the control of sagebrush in much of the country where that shrub has invaded the grasslands.

Although these methods are fairly effective, all of them are costly, and ranchers are constantly looking for cheaper ways to get rid of such noxious plants and save the water the plants use. Controlled burning, followed by reseeding, is being used increasingly to eliminate big sagebrush. In California, a new technique has been developed for the control of many of the chaparral species. The brush is first mashed down in strips with a bulldozer, and then burned. This method reduces the hazard of burning large areas and opens up the stand to natural recovery or for the reseeding of grass.

The most promising methods for the control of woody plants on range lands appear to be those that make use of selective herbicides. No completely satisfactory brush-killing chemical had been found up to 1955, but 2,4-D and 2,4,5-T have given the best results on the greatest variety of plants. Results have been erratic. Reasons for such differences are not entirely known, but they appear to be due to variations in temperature, moisture, and soil conditions and to variations in growth conditions of the plants at the time of application. The two compounds are usually most effective if applied in the spring at the time of the lowest ebb of stored food reserves and when the plant is growing most actively. Diesel oil is commonly used as the carrier for the chemicals, although some research indicates that water serves just as well.

Costs of application vary, depending on the size of the area to be treated, type of brush, roughness of the terrain, and, if airplane equipment is used, the distance to landing facilities. The cost of sagebrush eradication in Wyoming has averaged between 5 and 7 dollars an acre for materials and airplane application. Hand spraying of land heavily infested—400 trees to the acre, with post oak, blackjack oak, and winged elm—in Texas cost 27.23 dollars an acre. In both instances, the operations were well worth the cost. On the sagebrush land, forage production increased 20 to 85 percent after the first year and 100 to 200 percent 2 years after treatment. In Texas, with its greater rainfall, yields of forage following poisoning of the oak woodland were 5 times greater than on untreated areas.

CONTOUR FURROWING of range lands, especially those in poor condition, is done for two purposes—as a measure to conserve water to store the rain where it falls and stimulate forage growth, and as a way to protect lower lying lands and improvements from overflow and consequent siltation. The size and spacing of contour furrows will depend on which of these purposes is of first importance.

Ranchers have found furrows especially effective as a water-conservation

measure on shortgrass ranges that have developed after the taller growing grasses have been driven out by too heavy use. Under such conditions, the furrowing opens up the sod and permits more rapid recovery of the taller, more productive, midgrasses. Furrows may also be useful during periods of severe drought. At such times the furrows hold the little moisture that falls, enabling the vegetation close to the furrows to regain its vigor, produce seed, and thus speed up the general recovery of the range.

Contour furrows are more effective on less permeable soils because they catch storm water that would ordinarily run off under such conditions and save it for plant growth. They are of little use on sandy land, where they quickly fill up and lose their effectiveness. Contouring slopes in excess of 20 percent is hazardous, and, unless the furrows are properly constructed, the impounded water is likely to overtop them and cause serious erosion.

Small furrows, from 4 to 6 inches in cross section and spaced not more than 5 feet apart, are more effective than larger furrows or more widely spaced furrows. The small furrows regrass more rapidly and hold the water where it is of the most benefit. Larger furrows regrass slowly if at all, hold more water than can be used in one place, and, if they are widely spaced, tend to increase the aridity between the furrows.

The amount of range improvement from furrowing will vary with soil conditions, the amount and frequency of the rainfall, and the kind and condition of the vegetation. Over a 10-year period, contour furrowing reduced the annual runoff as much as 90 percent and at the same time increased the forage production 20 percent or more on ranges in Wyoming. Even with such proved benefits, considerable care should be exercised before undertaking furrowing operations to be sure the same results cannot be obtained by less expensive means. Thousands of acres of range lands have been furrowed needlessly when even more improvement could have been obtained at practically no cost by leaving more vegetation on the ground.

Range pitting is an effective water-conservation practice in arid regions, especially where range conditions are poor and the moisture from the sporadic rainfall is almost entirely lost through evaporation or runoff. The equipment commonly used is a heavy, 18-inch, one-way diskplow, with the alternate disks 20 inches in diameter and mounted 2 inches off center. The equipment scoops out shallow, discontinuous pits about 16 inches apart. The capacity of the pits on an acre thus treated is roughly 1,000 cubic feet, and they will hold about 0.3 inch of rainfall. In regions where the rainfall is normally insufficient to permit establishment of seedlings, treatment of the range by this practice may be the only means available to provide enough moisture for the young plants. Pitting may also be used in connection with reseeding, and under conditions of extreme drought may mean the difference between success and failure of such operations. If the range is pitted before seeding, enough moisture may be retained from the little rain that falls to enable the young plants to live through the critical spring.

Range pitting has a number of advantages over contour furrowing. Pitting does not need to be exactly on the contour and, since the depressions are small, there is little danger of increasing the erosion hazard. Moreover, revegetation is normally more rapid over the range as a whole, as the pits are distributed uniformly. Range pitting has the disadvantage, however, of requiring special equipment that may not be readily available.

To the rancher, the principal value of both contour furrows and range pitting is that they make possible the maximum use to be made of intermittent rains during the dry seasons when the natural grass cover is sparse and full utilization of moisture is vital.

A system of dikes and other struc-

tures designed to divert storm waters from stream channels and spread them over depleted, but potentially productive, areas is another effective means ranchers have found to save water on range lands. Such systems are more common on semiarid ranges, where the sparse vegetation encourages rapid runoff. They are also adapted to many other areas subject to flash runoff. The two basic requirements of an effective water-spreading system are an available flow of water and an adjacent area of suitable land on which it may be spread.

Since the system operates automatically whenever there is runoff storm water, considerable care must be taken in selecting a drainage area suitable for a water-spreading system. If the watershed above the spreading area is too large, the flow during storm periods is likely to be unmanageable, with danger of damage to the diversion structures. On the other hand, a small watershed may not produce enough water or flow frequently enough to justify the cost of building the system.

Besides the size of the watershed, a number of other features are important. If the drainage area is short and wide, with steep slopes, the runoff period will be over quickly, and there will be less opportunity to make effective use of the water. Watersheds where the gradient of the stream itself is steep should be avoided, as well as those where the stream normally carries considerable amounts of silt. Sediment carried onto the spreading area will tend to reduce water intake by clogging the soil surface. Such sediment deposits, if excessive, will prevent the vegetation from growing properly on the spreading area. The best drainages for water spreading systems usually are fairly long and narrow, with flat valleys (where any silt is deposited before reaching the spreading area) and ones where both the volume and frequency of flow are adequate.

Equal attention should be given to the selection of the spreading area. Slopes should be gentle. The flatter the land, the fewer the number of dikes required, the greater the area watered from each structure, and the less the cost of the system. Soils should be deep enough to absorb a large amount of water and sandy enough to take the water in quickly.

The design of the spreading system can be varied, however, to compensate for some soil differences. On very sandy soils the dikes should have a grade steep enough to distribute the water more rapidly and prevent too much of it from being absorbed in a limited area. Heavy clay soils, on the other hand, have a low infiltration rate and for such soils the gradient of the dikes should be less—to hold the water long enough to soak in. Spreading areas where the soils are heavily impregnated with alkali should be avoided, however. Even with added water, such soils do not usually produce enough additional forage to justify construction costs. Furthermore, dikes constructed with alkali soils tend to "melt" with every rain, and maintenance costs are excessive.

The most common type of a water-spreading system consists of a dam placed in the water course, with gradient ditches or terraces leading the water out to gentle slopes, where it is released through a system of dikes. Openings are left in the dikes so as to release a small amount of water at a time and increase the effectiveness of the system. With the water distributed automatically whenever there is storm runoff, the system should be so designed that the water will be released evenly over the land and not concentrate in low places to cause erosion. It is difficult on completely denuded areas to control a large amount of water without gullying. The structures therefore, should be designed to divert only the amount of water that can be controlled.

The construction of any practical water-spreading system is usually fairly costly. If the system is properly located and soundly designed, however, the benefits in increased forage and livestock production are likely to be con-

siderable. The benefits are usually more than adequate to recover the costs in a reasonable time. One rancher in Colorado estimates that, as a result of a series of water-spreading systems, his 30,000-acre ranch is producing 30 to 50 percent more forage than it did about 25 years ago. The estimate may be conservative. Increasing the forage from 5 to 10 times in 5 years through water spreading is not uncommon.

Water-spreading systems also improve the quality of the forage and increase livestock gains by lengthening the period the forage is green and succulent. This period may be expected to be from one to several weeks longer on a spreading area than on the drier range surrounding it. Besides increasing the forage by utilizing water that would otherwise be lost, water-spreading systems also serve the important purpose of reducing flood hazards and erosion losses.

MANY THOUSANDS of acres of western rangelands, because of overgrazing or cultivation, or both, no longer support good stands of native forage plants.

Improvement in the production of forage by means of livestock management alone may take a long time on them. In places where climate and soil conditions are suitable, reseeding with adapted grasses can quickly and economically improve deteriorated ranges. Improved forage production through range reseeding often equals and sometimes surpasses that produced by the original native forage plants.

Improved forage production is largely the result of more efficient use of the rainwater that falls on the land.

Deteriorated rangelands and lands abandoned after cultivation usually have only a sparse stand of vegetation. The stand often includes annual weeds and grasses, a few scattered plants of perennial grasses, and low-growing shrubs. Such lands seldom produce more than 50 pounds of palatable forage on an acre, and the cover is too sparse to insure that the maximum amount of rainwater soaks into the soil. The runoff waters have scoured the surface soils and have marked them with rills and gullies. Where water was once used for the production of forage, it now escapes downstream, often in damaging quantities.

Successful reseeding is not a simple operation. It costs 5 to 10 dollars an acre, depending on prevailing land conditions and upon the species of seed selected to plant. It requires careful seedbed preparation and planting, and generally the stand should not be grazed until two growing seasons have passed. There is also the ever-present hazard of accelerating erosion on the reseeded areas during the period of establishment. Once a stand is established, more rainwater soaks into the ground, and little or no erosion occurs.

Measurements of forage production on ranges reseeded separately to crested wheatgrass, smooth bromegrass, intermediate wheatgrass, and Russian wildryegrass show yields ranging from 1,000 to 3,000 pounds an acre. Those high yields are due in part to the more efficient use of rainwater, little of which runs off the soil surface and in part to the deep and fibrous root systems of the reseeded grasses. The root systems can absorb moisture to depths of 6 feet or more, while in the upper 3 feet the soil column is so permeated with roots that all of the available moisture is used for plant growth. So sensitive are the reseeded grasses to the availability of moisture that their annual forage yield will vary in proportion to annual precipitation. For example, the forage production of crested wheatgrass has varied from 2,100 pounds an acre, when the annual precipitation was 15.5 inches, to 600 pounds an acre, when the annual precipitation was 9.7 inches.

Field-plot observations in central Utah of the amount of water consumed and the amount of forage produced by pure stands of smooth bromegrass, timothy, Kentucky bluegrass, and a mixture of dandelion and sweetsage illustrate the efficiency of water use by reseeded grasses.

Smooth bromegrass consumed the most water but also produced the most forage and made the most efficient use of the water consumed. Forage yields amounted to 350 pounds an acre for each inch of water consumed. By comparison, timothy consumed 0.79 of an inch less water but produced only 135 pounds of forage an acre for each inch of water. Kentucky bluegrass consumed about an inch less water than the timothy but was more efficient, producing 210 pounds of forage an acre for each inch of water. The dandelion-sweetsage plots consumed about 1.6 inches less water than those with timothy; they were the least efficient in forage production and yielded only 80 pounds of forage for each inch of water.

Where climatic and soil conditions permit, reseeding deteriorated rangelands and abandoned cultivated lands is an effective means of increasing the efficiency of water use. Once those lands are reseeded with adapted grasses, more of the annual precipitation soaks into the soil and is available for forage production. A twentyfold increase in forage yield may result from reseeding operations on suitable depleted areas. The increase is due to the greater amount of rainwater entering the soil and to the inherent ability of the reseeded grasses to utilize water efficiently.

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Phreatophytes—a Serious Problem in the West

Herbert C. Fletcher and
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Phreatophytes occupy about 15 million acres of land in the Western States. They are plants that send their roots down to the water table or the capillary fringe just above the water table which provides a ready supply of water. The term, derived from two Greek words, means "well plant."

Semidesert vegetation generally has to adapt itself to an extreme water economy and grows mostly on moisture accumulated in the soil from winter snows and the infrequent summer rains. During drought periods, semidesert plants are essentially dormant, and so are able to survive.

Phreatophytes, in contrast, are water-loving plants that grow mainly along stream courses, where their roots reach into the capillary fringe overlying the water table. There they are able to get a lasting supply of water. These lush, green plants stand out in sharp contrast to the gray, semidesert vegetation that is denied this supplemental source of water.

Phreatophytes form a definite group of plants but do not belong to any specific family. Their common characteristic is their heavy use of a large supply of water.

Men who have studied the problem throughout the West realize that a large part of the water consumed by

phreatophytes could be put to beneficial use by replacing the phreatophytes with crops, grass, or other beneficial vegetation. They make a distinction between phreatophytes that are directly beneficial to man and those that consume water without returning commensurate benefits. Alfalfa, a plant that uses more water than most crops, is esteemed. Trees use large amounts of water, but some are essential as shade for livestock and homesteads, even in places where water is scarce. Dense growths of willows, saltcedars, or cottonwoods along stream channels exemplify the types of vegetation that use a lot of water but give little benefit. Only the objectionable phreatophytes are considered here.

Many persons believe that the high consumption of limited water supplies by phreatophytes is one of the most serious problems facing the irrigated West. Along the Rio Grande Valley in New Mexico, for example, the high consumptive use of water by saltcedars and other water-loving vegetation is a main reason why New Mexico has had difficulty in delivering water to Elephant Butte Reservoir, as required by the Rio Grande Compact.

As a rule, the transpiration of water by plants is greater than evaporation from bare soil and occurs from much greater depths. Roots of many plants lift water much higher than it can be lifted by the capillary action of the soil.

A few dominant species are responsible for most of the heavy use of water—saltgrass, *Distichlis spicata;* greasewood, *Sarcobatus vermiculatus;* saltcedar, *Tamarix gallica;* cottonwoods, *Populus spp.;* baccharis, *Baccharis glutinosa;* willows, *Salix spp.;* and mesquite, *Prosopis juliflora*. All occur in the valley bottoms and along streams.

The ground water level in some localities declines during the day and rises at night with clocklike regularity because of the high water requirements of the plants. G. E. P. Smith, of the University of Arizona, determined in 1916 that the daily fluctuations in one well in the San Pedro Valley were due to a forest of mesquite and in another well to a grove of cottonwoods.

Walter N. White measured wells in the Escalante Desert in Utah in 1927 and observed that the water table fluctuated every day during the growing season wherever concentrations of phreatophytes occurred. The water began to drop in the wells between 9 and 11 a. m. and reached its lowest point between 6 and 7 p. m. After sundown the water began to rise, continuing until 9 o'clock the following morning. The size of the daily fluctuations varied with the stage, vigor, and density of plant growth. When the plants stopped growing because of killing frosts, the fluctuation stopped. The seasonal discharge of ground water by plants surrounding the wells amounted to 27.2 inches of water for alfalfa, 22.0 inches for saltgrass, 3.1 inches for shadscale, and 2.6 inches for greasewood.

The report of the Rio Grande Joint Investigation in 1936 directed attention to saltcedars as important consumers of water. From studies made by the Department of Agriculture in 1940, the National Resources Planning Board concluded that the average consumption of water on the Pecos River delta above McMillan Reservoir, occupied by a dense growth of saltcedars, was about 5.0 acre-feet annually, derived from ground water, surface water, and precipitation.

In 1943 and 1944 the Geological Survey studied the consumption of water by saltcedars, cottonwoods, willows, baccharis, and mesquite in the Safford Valley of the Gila River Basin. Results of the study were reported in *Water Supply Paper No. 1103*, published in 1950.

The report stated that the consumption of water in the 12 months that ended September 30, 1944, for 9,303 acres in a 46-mile stretch of the Gila River Channel was 28,000 acre-feet, an average of about 3.0 acre-feet an acre. About 23,000 acre-feet came from ground water and about 5,000 from precipitation. The density of the vegetation was about 52 percent. If

the density had approached 100 percent, which occurs in some infestations, the annual consumption may have been much higher.

A. A. Young and Harry F. Blaney, in a summary of the results of studies up to 1942, pointed out the wide range in annual use of water by different plant species. Part of the difference was attributed to species, part to the depth of the water table, part to climate, and part to geographic locations.

A saltgrass meadow in southern California, for example, lost 13 inches of water when the water table was 4 feet below the soil surface and 43 inches of water when the water table was 1 foot below the surface. Another area lost 24 to 49 inches of water as the water table rose from 4 feet to 18 inches below the ground surface. The maximum range in water loss was 10 to 49 inches. Tules and cattails lost 90 inches of water a year, when the water table was at the surface in central California, and 121 inches in the Mesilla Valley in New Mexico. Willows used between 30 and 53 inches a year. Sedges and rushes used about 77 inches.

As a general rule, the shallower the water table the higher the rate of use. The depth to the water table controls the occurrence and growth of most species. Saltgrass generally grows best when the water table does not exceed 6 to 8 feet and will survive when the water table is as low as 12 feet. Greasewood grows best in places where the water table does not exceed 15 feet. Mesquite has been known to send its roots 40, 50, or even 100 feet to water. Saltcedar, willow, and cottonwood prefer localities where the depth to the capillary fringe is about 10 feet, but it will go down to 20 feet.

The depth of the capillary fringe has a great deal to do with the survival of the plants. It is affected by the texture and structure of the soil profile above the water table. Fine-clay soils have a greater depth of capillary fringe than coarse, sandy soils. Consequently, in areas of fine-textured soils, the capillary fringe may come within the reach of the shallower rooted plants even though the water table is many feet below. That may also explain why saltgrass, one of the shallower rooted plants, grows where the water table is 10 to 12 feet below the surface.

Climatic conditions closely control the occurrence and growth of some species, but not all. Saltcedar, mesquite, and baccharis grow best in a moderate climate south of the 37th parallel and below 5,000 feet elevation. Willows, cottonwood, and saltgrass cover most of the Western States from Canada to Mexico wherever ground water conditions are favorable. Saltcedar is quite sensitive to climate. It is found as far north as Nevada, but there it seldom spreads over large acreages; in Arizona and New Mexico it exhibits a very vigorous, junglelike growth on many of the major stream courses. Greasewood prefers the cold desert areas, generally north of the 37th parallel. Greasewood and saltcedar therefore seldom occur together.

Other factors that limit the growth of phreatophytes are length of growing season, hours of daylight, temperature, rainfall, and humidity. The draft on the water supply is greatest during a long, hot growing season, with scanty precipitation and low humidity.

The quality of the ground water also affects the growth and the rate of water use. Generally, the higher the mineral content, the less vigorous is the growth. Some plants, such as willow, grow only where the mineral content of the water is low.

Others, such as saltcedar, greasewood, and saltgrass have a high tolerance for mineralized water. In areas where the mineral content of the ground water is low, the concentration of the salts in the surface soil generally is also low. In places where the mineral content of the ground water is high, the concentration of salts in the surface soil may become so toxic that even the most alkali-resistant plants cannot survive. Thus mineralization conditions greatly affect the

density and vigor of the vegetation and its ability to use large amounts of water.

Few studies have directly demonstrated how much water could be saved from evapotranspiration loss by the removal and replacement of phreatophytes. The actual amount of water saved for use elsewhere by removing the phreatophyte vegetation is still largely a matter of conjecture. Many estimates of water use by phreatophytes have been made for individual areas. It may not be practical or desirable to recover all of the water because the vegetation using it gives some protection against erosion. Little research has been done to determine water use by vegetation along mountain streams. Information on the point is fragmentary and does not consider the possibilities of increasing the amount of water by eradicating phreatophytes.

Work of this type has been started at the Sierra Ancha Experimental Watersheds about 40 miles north of Globe, Ariz., to determine the effect of different types of timber cutting on streamflow.

Two other studies provide measurements of evapotranspiration losses along mountain streams. A. R. Croft's studies in the Wasatch Mountains in northern Utah showed that evapotranspiration losses from Farmington Creek amounted to one-third of the total streamflow from August to October. In Cold Water Canyon in California, Young and Blaney measured the water losses along 8,000 feet of canyon bottom and found that in the 4 months of July-October, 1932, the upper part of the channel lost 38.5 inches of water for the area of phreatophytes and the lower reach of the stream 46.6 inches.

The studies indicate the economic feasibility of eliminating some of the loss by piping the water through some of the channels of highest use or by keeping vegetation to a minimum along stream channels.

Acreages covered by phreatophytes and estimates of annual water use were made for some Western States in 1953 by T. W. Robinson of the Geological Survey:

State	*Area (Acres)*	*Annual use (Acre-feet)*
Arizona	405, 000	1, 280, 000
California [1]	317, 000	1, 150, 000
Colorado [1]	737, 000	1, 056, 000
Idaho	500, 000	1, 000, 000
Montana	1, 600, 000	3, 200, 000
Nebraska [1]	515, 000	709, 000
Nevada	2, 801, 000	1, 500, 000
New Mexico	300, 000	900, 000
North Dakota	1, 035, 000	1, 660, 000
Oregon [1]	40, 800	21, 200
South Dakota	850, 000	1, 240, 000
Texas [1]	262, 000	436, 500
Utah	1, 200, 000	1, 500, 000
Wyoming	527, 000	1, 100, 000
Total (approximate) [2]	11, 090, 000	16, 750, 000

[1] Partial data, from published reports on areas within the State.

[2] Partial data.

WHILE IT APPEARS feasible to salvage at least part of the water used by phreatophytes, development of methods for doing so have not passed the experimental stage.

To recover the water, the vegetation must be removed or the water supply must be taken from it. Removal of the vegetation by mechanical means, burning, chemical sprays, or other methods generally is only temporary, if other conditions are unchanged. Permanent control can be achieved only when the water supply is removed from the plants by lowering the water table, piping the water across the area, or cutting off the supply from above.

Two control measures often applied are burning and mechanical control, but they are only temporary measures, because most species sprout vigorously. In the Safford Valley of Arizona, attempts were made to control saltcedar by burning and by uprooting the plants with heavy equipment. The operations tended to stimulate the remaining roots to greater activity, and by the end of the next growing season new growth was 5 to 6 feet high.

Extensive field tests have been made in New Mexico to control phreatophytes, particularly the saltcedar and willows, with chemical weedkillers. On

100 acres of the delta in McMillan Reservoir, saltcedar was sprayed twice by airplane, once in September 1948 and again in June 1949, with an oil-water emulsion of the sodium salt of 2,4-D at the rate of 1 pound acid equivalent an acre the first year and 2 pounds the second year. The chemical, applied at the rate of 5 gallons of spray an acre, consisted of 4 gallons of water and 1 gallon of diesel oil. By the fall of 1950, regrowth varied from as little as 1 percent in some areas to 100 percent in others. The general overall kill was about 85 percent. On another area, sprayed in the fall of 1948, 1 pound of 2,4-D (acid equivalent) to the acre gave only 30 to 40 percent kill, and growth the following year was considerable.

Control of willows by mowing in the fall and spraying the regrowth the following spring has given good results along the Rio Grande canals above El Paso, Tex. In mid-April, after regrowth had started, the area along the banks was sprayed with a mixture of sodium salts of 2,4-D in solution containing 1.5 pounds of acid equivalent, 1 pint of Triton X–100, 5 gallons of diesel oil, and 95 gallons of water. It was applied at the rate of 100 gallons an acre.

Marked results were evident within 15 days after treatment, when 90 percent of the growth was killed. The small amount of regrowth that occurred was easily taken care of by repeated applications of the same mixture during the regular maintenance program.

Research by H. Fred Arle, of the Agricultural Research Service, in the Gila River channel near Phoenix, Ariz., indicated that 6 or 7 applications of chemical sprays may be needed to kill saltcedar. Fall and spring treatments started in 1951, using a high rate of amine 2,4-D; only 63 percent of the plants were killed with 6 spray treatments. Plots started a year later had 5 treatments; 52 percent of the plants were killed. Plots started in 1952 with only 3 treatments had only a 3-percent kill by 1954. Other plots sprayed in 1951 with esters of 2,4-D and 2,4,5-T showed a kill of 100 percent after 6 treatments. On plots started in the spring of 1952, 5 treatments killed 69 percent of the plants. Plots started in the spring of 1953 had only 16 percent of the plants killed. Two rates of application were used in both instances—1.25 and 2.5 pounds acid equivalent to the acre.

The figures indicate the superiority of the ester formulation of 2,4-D plus 2,4,5-T over the amine formulation of 2,4-D. The higher rates of applications resulted in greater kills with the same chemical. The studies also indicated that saltcedar increases its resistance to herbicides with continued treatment as the time interval from the first treatment lengthens.

New formulations of 2,4-D and 2,4,5-T, such as the butoxy ethanol and the propylene glycol butyle ether esters, are more volatile than the amine and sodium salts. First experimental results on woody plants indicate that the high esters equal or surpass the amine, sodium, and low-ester formulations in effectiveness and are somewhat less hazardous to use in places where sensitive crops are grown.

One must be careful in applying chemical sprays near agricultural crops, many of which—especially cotton—are highly sensitive to the sprays.

In two situations chemical spray treatments appear to hold promise in controlling phreatophytes. One is on flood plains, around the heads of reservoirs, and in other places where the chief aim is to reduce loss of water by killing the vegetation. The other is in floodways and stream channels which have been cleared mechanically, and must be kept free of phreatophytes from old roots or seedlings.

More information, however, is needed on rates and relative effectiveness of the different formulations of 2,4-D, 2,4,5-T, and other growth-regulating chemicals before definite recommendations can be made as to their use.

Before we can reduce the use of water

by substituting one type of vegetation for another we need to know more about the use of water and growth of phreatophytes and the requirements of the substitute plants. In a locality of highly alkaline soil, attempts to substitute a plant having a low tolerance for alkali would fail. Forage crops, particularly alfalfa and grasses, seem to be best adapted for the purpose. Alfalfa was successfully substituted for an association of greasewood, rabbitbrush, and saltgrass in the Escalante Valley in Utah. There is no simple method or solution to the problem of controlling phreatophytes. Each area needs intensive study to understand its particular requirements.

Many persons have been interested in the possibility that phreatophytes in large valleys may keep sediment from going into storage reservoirs. They have been impressed by the growth of large, dense thickets of saltcedar, willow, cottonwood, and other phreatophytes on deltas formed by sediment deposited at the heads of large reservoirs. The association of the phreatophytes with the sediment cannot be denied.

But whether holding the sediment out of the main part of the reservoir outweighs the water they use is questionable. The heavier riverborne sediments are deposited where the current meets the pool of stored water, at the head of the reservoir. Deltas have preceded the invasion of phreatophytes in many places; in other places, phreatophytes have been responsible for the deposition.

Phreatophytes and other vegetation reduce the velocity of the water that flows through them and thereby screen the heavier sediment out of the water. Some authorities have suggested that it may be worthwhile to plant useful vegetation above the heads of reservoirs to help check the sediment before it reaches the main storage basin and thus prolong the life of reservoirs. Several types of low-growing shrubs that are easily controlled and would provide food for wildlife have been suggested for the purpose, among them wild rose, *Rosa multiflora;* sand cherry, *Prunus Besseyii;* hackberry, *Celtis pallida;* and Russian-olive, *Elaeagnus angustifolia.*

The ability of various grasses to withstand sedimentation and still survive and reestablish an erosion-resistant cover has rated them high as replacements for the higher water-consuming plants.

Strong rhizomatous grasses probably are best adapted to withstand the heavier deposits of sediment, because, within limits, they are capable of regrowth by rhizomes to the surface.

Well established stands of large bunch grasses, such as large sacaton, *Sporobolus giganteus,* and salt sacaton, *Sporobolus airoides,* can survive rather heavy deposits of sediment. Several other grasses may be able to withstand deposition of silt. One is blue panicum, *Panicum antidotale,* which seems to be adapted to the warmer climates. Others are reedgrass, *Calamagrostis epigeios,* and species of elymus from China and Australia. Grasses such as these, established in a replacement program, could be used for hay or pasture. It should be remembered, however, that measures for controlling the large loads of sediment in our major streams are only stopgaps until our watersheds can be rehabilitated with a practical cover of vegetation that can be maintained in good condition.

Various assertions have been made as to the value to wildlife and cattle of phreatophytes growing in river bottoms. The most objectionable phreatophytes spread fast and cover large areas with dense thickets. Usually the thickets furnish little food for game, however. More desirable species that are easily controlled will furnish more food, protection, and other benefits for wildlife and livestock than do saltcedar, cottonwood, and some kinds of willow—and will furnish the benefits at a much lower cost in water.

Some studies have been made of the potential savings of water from the

eradication of phreatophytes. The consumption of water by nonbeneficial phreatophytes in Nevada was estimated at 1,500,000 acre-feet a year. About 25 percent of that amount, or 375,000 acre-feet, was estimated to be salvageable—enough to irrigate 133,000 acres of alfalfa. Another example is the proposed channelization of the Gila River past Phoenix, Ariz. The Corps of Engineers and the Geological Survey estimated that keeping a floodway 2,000 feet wide and 77 miles long free of phreatophytes would save an average of 16,000 acre-feet of water annually. Another estimate was made by the Engineering Advisory Committee to the Pecos River Compact Commission in 1948. If the 15,000 acres of saltcedar growing on the delta above McMillan Reservoir could be eradicated and controlled or bypassed by channeling, an additional 39,000 acre-feet of water annually might be added to the water in the Pecos.

Work by the Bureau of Reclamation in channelizing the Rio Grande for about 32 miles above Elephant Butte Reservoir shows that considerable water can be saved for downstream use. This section of the Rio Grande Valley was heavily infested with cottonwoods, willows, and saltcedars, whose estimated yearly consumption was about 150,000 acre-feet. Previously almost no channel existed for considerable distances, and much of the river discharge was lost without reaching the reservoir.

A new low-water channel lowered the water table 8 to 10 feet on the average. Two years after completion of the first contract and before the entire project was finished, water flowed into Elephant Butte Reservoir during the winter and at other periods of the year when normal river flows formerly failed to go through that section. After the channel was made, approximately 100,000 acre-feet of water reached the reservoir. The increased river discharge was streamflow that would probably have been lost under former conditions.

Phreatophyte-covered lands of the West represent another goal for more effective land management. Most public interest in phreatophytes has centered on the enormous amount of water they use and possible water savings that may be realized if they are removed. When they are controlled, additional water will be available to supplement present supplies. Studies indicate that the economic benefits from substituting irrigated crops and productive grasses for phreatophytes would more than balance costs. While we do not yet know the most economic method of salvaging water used by phreatophytes we do know that by conserving this water for crop production, irrigated agriculture of the West will be benefited.

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Irrigation Practices for Pastures and Forage Crops

John R. Carreker and James H. Lillard

The cost of irrigating pastures and forage crops may be relatively high because they have long growing seasons and may therefore need more frequent applications of water than most other crops. Pastures and forages also are relatively low in value, and the farmer has to get bigger yields if irrigating them is to be profitable.

It is important therefore that other crop management practices be maintained. Irrigation should supplement but not replace other good farming practices.

High-yielding and highly nutritive species and mixtures can be used to enhance the probable returns from irrigation. Studies dealing with feeding, processing, and storing the sod crops have pointed the way to their more efficient use on various types of farms.

Pasture and forage produced with plenty of moisture generally are slightly higher in feeding value and are better liked by animals.

WATER IS APPLIED to pasture and forage crops by flooding, sprinkling, and subirrigating.

Flood irrigation may be done in several ways—by border checks, contour checks, and furrows. Generally topography and soil conditions dictate which one. Flooding is used mainly in the Western and Southwestern States.

The land must be thoroughly worked before seeding and uniformly leveled to permit even application of the water and prevent dry high spots and too wet low spots. Proper leveling cuts the work of getting the water over the land and makes for better irrigation.

Water moves over sod more slowly than it does over land in other crops. It also enters the soil faster. Larger heads of water are needed therefore for sod crops than for other crops when surface methods are used.

Border irrigation usually is recommended on uniform slopes of 3 percent or less. Flooding from field ditches is used on uneven topography and steep slopes.

Sprinkler irrigation is good on land too rough or too shallow to be leveled, on very porous soils, and in places where water is too scant for effective flooding.

Positive control of application rates and amounts can be had with sprinkler systems through good engineering design. The amount and rate can be held to the amount that can be stored in the soil within the root zone of the crop without causing runoff, erosion, or deep seepage.

Sprinkler irrigation can be used under any practical farm conditions where a water supply is available. The first cost of the pump, power unit, pipe, and sprinkler is high. Later costs of power and labor usually make sprinkler irrigation more expensive than flooding.

Subirrigation is practiced on only a limited acreage—mostly on favorable sites in Florida and along the Atlantic coast to New Jersey.

Maurice L. Petersen and Robert M. Hagan, of the University of California, found that about 92 percent of the pasture and grassland irrigation in the western part of the United States is done by flooding and 8 percent by sprinkling. In the subhumid parts of the Midwest, both flooding and sprinkling are used rather extensively. Most irrigation in the humid East is applied by the sprinkler method. Flooding is used rarely.

TIMING OF IRRIGATIONS in relation to stage of growth of pastures and meadows requires further investigation. Research in South Carolina, Virginia, and other States indicated that on field crops, such as corn and tobacco, fewer applications of water applied at critical stages of growth gave results as good or almost as good as continuous

irrigation. We need to find out whether such economies are possible with the sod crops.

The comparatively shallow root system of most forage crops limits the amount of water that can be stored in the root zone area of the soil profile. More frequent and relatively small applications are needed to maintain a favorable moisture balance.

Except in the dry and high mountain areas of the West, irrigation of pastures and meadows is needed most in the middle and latter part of the growing season. Winter precipitation normally fills the soil profile enough for the first spring growth. Supplemental irrigation is used thereafter to supply deficits in natural rainfall. Irrigation must be supplied to start spring growth in the drier regions.

If rotation grazing is practiced, irrigation (if the extra water is needed) should be timed so that the applications are made several days before the cattle are turned into a pasture and immediately after they are removed. It is important that ample soil moisture be available to hasten regrowth immediately after a hay crop is removed.

THE EFFECT OF SOIL MOISTURE LEVEL on quality and yield of pastures and hay crops has been the subject of a great deal of research.

Irrigation schedules are affected by the rooting habits of the crops, the water-holding capacity of the soil, the peak moisture use, the crop-water relationships, and rainfall.

In regions of little or no rainfall the schedules can be reasonably uniform in frequency and amount. The time of water delivery to a farm in the Western States often determines the frequency of irrigations. Schedules in the humid areas are largely controlled by the amount and distribution of rainfall during the growing season.

The depth of the root system of the plants limits the zone from which moisture for plant growth can be extracted. The water-holding capacity of the soil profile within the effective root zone determines the volume of water that can be stored for future growth needs.

The peak moisture use controls the rate of depletion of soil moisture and, together with intervening rainfall, determines the irrigation frequency. The growth characteristics of the crop or mixture at different soil moisture levels affects the selection of the proper moisture level to begin irrigating. The species having the shallowest root system generally controls the irrigation schedules, because it will require irrigation oftener than species with deeper roots.

Little research has been reported on the effect of moisture stresses on the growth of pasture mixtures or forage crops other than alfalfa. W. H. Daniel, at Michigan State College, reported that yields of red fescue and bluegrass harvested by close clippings, were highest when frequent irrigations were applied.

Dr. Petersen and Dr. Hagan reported that studies at the University of California on the effect of moisture stresses on the growth of Ladino clover showed that frequent irrigation produced more fresh weight but little more dry matter than did plots that received less frequent irrigations but had some available moisture in the soil at all times. They concluded that the most economical point to irrigate is when 75 percent of the available moisture in the effective root zone has been depleted.

Field practices in most humid areas are in keeping with those conclusions. Irrigation usually is started when about 50 percent of the available moisture is gone, so that the entire field can be covered before the available moisture is entirely depleted from the last section reached.

Other research indicates forage yields are higher and plants more succulent for grazing when moisture is ample. R. R. Robinson and V. G. Sprague, in studies at the Pennsylvania State University, measured yields of orchard grass-Ladino clover of 5,770 and 2,950

pounds an acre on a moisture-free basis, with and without irrigation, respectively, when no nitrogen fertilizer was used. The addition of nitrogen at 260 pounds an acre with irrigation and 220 pounds an acre without irrigation increased the yields to 8,050 and 6,020 pounds an acre, respectively.

G. E. McKibben and others conducted research at the University of Illinois, which showed that Ladino clover and grass stands were maintained successfully with irrigation. But without irrigation the clover was overgrazed in preference to the grass during dry periods, and only grass remained in the pasture.

Comparisons at the Dairy Experiment Station, Lewisburg, Tenn., between irrigated and unirrigated pastures consisting of orchard grass, Ladino clover, and alfalfa, included records of returns of milk sales from cows on each pasture. Gross returns per acre per year for the 3-year period 1951–1953 were 552 dollars with irrigation and 364 dollars without irrigation. It cost 50 dollars an acre to apply the irrigation water each year. The stand of Ladino clover was almost gone after 3 years on the unirrigated pasture, but a good mixture of species was maintained with irrigation.

John R. Carreker, W. J. Liddell, and H. B. Henderson, at the University of Georgia, concluded that the grazing days on an acre and the weight gains of animals were greater on irrigated than on unirrigated pastures. Half-grown dairy heifers grazed summer pastures of Dallis grass and Ladino clover. The number of animal days per acre of grazing was increased from 280 a year without irrigation to 372 a year with irrigation. The weight gain per acre per year was 315 and 395 pounds without and with irrigation, respectively. The water applied averaged 7.75 inches a year in 5 applications for the 4-year period from 1947 through 1950.

Other studies by Dr. Petersen and Dr. Hagan at Davis, Calif., showed that frequency of clipping affected markedly the quality and yield of forage. The forage crops included in the study were mixtures of four grasses and different legumes. The grasses were annual ryegrass, perennial ryegrass, orchard grass, and alta fescue. Legumes included broadleaf trefoil, Ladino clover, and alfalfa and a mixture of the three. Clippings were made at intervals of 2, 3, 4, and 5 weeks. Forage yields increased as the time between harvests was lengthened. Rotational grazing on the mixtures was recommended, with intervals between grazing periods of no less than 25 days for the Ladino clover mixture and somewhat longer with the other mixtures.

J. Nick Jones, Jr., C. M. Kincaid, and their associates at the Virginia Polytechnic Institute found that irrigation increased grazing days 43, 49, and 60 percent for beef animals and individual steer gains of 32, 70, and 42 pounds in 3 out of 5 years. The amount and distribution of rainfall in 2 of the 5 years was such that little or no irrigation was needed, and no significant responses were obtained from the extra water applied. The net amount of irrigation applied was 7.4, 7.0, and 11.2 inches in the three drier years. The pasture mixtures included bluegrass-white clover and Ladino clover-orchardgrass on a well-drained silt loam soil of limestone origin.

From the results it was concluded that in Virginia and places of like climate the best possibilities for the profitable use of irrigation in the production of beef lies in its use on limited acreages of high-producing forage mixtures grown mainly for hay or silage but available for supplemental pasture as needed during dry periods.

Other studies by Mr. Jones, J. E. Moody, and R. E. Blaser in Virginia have shown significant advantages for irrigation in maintaining pasture mixtures through the frequent midsummer and late summer droughts. The maintenance of a favorable soil moisture balance was found to promote much more even growth throughout the sea-

son than generally is had from rainfall alone.

Results of pasture irrigation in New York parallel the research in Virginia. The agricultural engineers and agronomists who conducted the studies believe that irrigation of pasture and forage crops will pay only in seasons that are drier than normal. In one experiment in New York, where three rates of fertilizer were used on a Ladino-orchardgrass mixture, the 4-year average increase in dry matter production from irrigation was 0.44, 0.28, and 0.05 tons an acre, respectively, for the low, medium, and high rates of fertilization.

THE AMOUNT OF WATER used by crops, sometimes referred to as consumptive use or evapotranspiration, depends on the weather conditions more than on the extent and type of vegetation.

E. J. Russell, in a review of experimental work at the Rothamsted Experimental Station in England, concluded that the amount of water a crop transpires depends on the amount of water available to the crop during the period of the day when the stomata—the tiny pores—of the leaves are open and on the solar energy that reaches the crop. For turgid crops with open stomata, the amount of water transpired depends on the energy available. Most of the energy absorbed by the leaves that is not reflected or re-radiated is used to evaporate water. He concluded further that water used by plants for photosynthesis comprised less than 1 percent of the total evapotranspiration.

Drs. Hagan and Petersen found that rates of consumptive use were little affected by the botanical composition of forage crops. Several different grass and legume mixtures used nearly 0.3 inch a day during the hot, dry months of July and August. They found a definite pattern of water extraction from soil by different botanical mixtures. Moisture extraction by a mixture of Ladino clover and grass was largely confined to the top 4 feet of soil; with a mixture of Broadleaf trefoil and grass, appreciable extraction occurred throughout a 6-foot depth of soil. The consumptive-use rates were little affected by height of regrowth or clipping most of the tops of the plants.

A. G. Van Horn found the water requirement of the orchardgrass-Ladino clover pasture at the Dairy Experiment Station, Lewisburg, Tenn., was about 2 inches each 10 days for the 7 months of April through October.

G. E. McKibben and others at the University of Illinois found that additional water was needed to maintain maximum growth of a grass-legume mixture when the rainfall dropped below 2 inches in 2 weeks in summer.

Mr. Moody and others at the Virginia Agricultural Experiment Station found little or no difference in the consumptive-use rates by bluegrass-white clover and orchardgrass-Ladino clover pastures. Two inches of water each 9 days during the summer were needed to maintain a favorable soil-moisture balance in the root zone of those sods.

ANNUAL CROPS sown for temporary grazing or hay may be benefited by irrigation. Their success depends on quick germination, rapid growth, and early maturity. Water applied during short droughts insures those results.

Winter annual grazing crops are popular in the South where the climate is mild. They include the small grains, clovers, vetches, and others alone and in combinations. The normally dry weather in the fall often delays their planting date, germination, and growth. Irrigation then insures planting on time and rapid and continued growth. That gives more forage earlier in the winter.

Research at the University of Georgia disclosed that irrigating oats and crimson clover after seeding in September and in October advanced the first grazing date from February to the middle of November and increased forage production 200 percent.

Summer crops like sudan grass and millet respond well to applications of

irrigation water during droughts. Research workers at the Mississippi Agricultural Experiment Station measured green-weight yields of sudan grass equal to 21.4 and 10.1 tons an acre with and without irrigation, respectively. Similar measurements showed the yield of millet to be 20.6 and 8.9 tons an acre.

MANAGEMENT PRACTICES necessary with irrigation of pasture and forage crops vary with the method of irrigation employed. Fertilization and management of crops and soils, however, are primary considerations wherever irrigation is used. Land leveling and seedbed preparation must be performed with high precision in the western flood-irrigated areas. Adequate provisions for drainage and salt control also are necessary. Control of runoff and erosion must be considered in the plans for irrigation on rolling terrain, particularly in the humid areas.

Basic research concerned with soil-water-plant relationships has been intensified in recent years. Some data are already available to aid in the selection of species and mixtures on the basis of soil adaptability, growth habits, and water requirements so that high production will be uniform all season.

Dr. Blaser and Mr. Moody found from studies of supplemental irrigation on 14 species and mixtures that much of the midsummer slump in production of the various grasses and legumes can be minimized by maintaining optimum moisture conditions.

They found also that in Virginia the amount of legume seed in the various mixtures of legumes and tall grass must be reduced if irrigation is used in order to obtain and maintain properly balanced mixtures.

Limited research indicates the desirability of increasing the fertilizer rates above those considered optimum without irrigation. Site conditions, such as soil productivity, the species of plants, and the management practices, govern the maximum practical rate of fertilization that can be used profitably with irrigation.

If moisture is ample for uniform growth rates, grazing schedules can be gaged to utilize efficiently all growth at the stages in which it is most nutritious. Likewise, harvesting schedules can be established to gain all possible quality and yield advantages from hay and silage crops. Irrigation of pastures makes it possible to practice the most appropriate system of controlled grazing. Schedules can be established and followed with assurance of efficient results. Selective grazing is minimized, quality is better controlled, and losses of feed by periodic maintenance clippings is reduced.

Irrigation permits the maintenance of a proper balance of grass and legumes in pasture and forage mixtures over a longer period of time than is possible under normal rainfall conditions in most areas. The resulting thicker sods further enhance the natural ability of pastures and meadows to conserve water and soil.

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Irrigation Practices for the Production of Alfalfa

C. O. Stanberry

Eight hundred tons of water may be required to produce a ton of alfalfa hay. Alfalfa stands drought well, but it requires more water than most crops because of its rapid and heavy growth and number of cuttings. One-fourth of the 20 million acres of alfalfa in the United States was irrigated in 1955.

The three most common methods of irrigating alfalfa are by corrugation, border, and flooding. Each is adapted to a particular set of conditions according to water supply, soil, and climate.

Basin, sprinkler, and subirrigation methods are also used. An irrigation efficiency of 70 percent for alfalfa is good; in many places not more than half the water delivered to the farm is utilized by the alfalfa plant.

THE ESTABLISHMENT of the stand justifies special attention because much labor and water are required during the 3 years or more that the stand lives. Irrigation is facilitated if the seedbed is prepared with a uniform grade.

Alfalfa succeeds on a variety of types of soil. Deep, well-drained loams with a high capacity for absorbing and storing water are most desirable. Soils with slow rates of penetration are less well suited.

Adequate phosphate fertilizer should be incorporated when the seedbed is being readied. Applications of nitrogen fertilizer for stand establishment frequently encourage weeds.

Alfalfa is usually planted in fall or spring, when loss of moisture from the soil surface is not rapid—in August and September or in March through May in the Northern States and in September and October or in February to mid-April in the South. Fall seedings are favored in many places because the danger of wind damage then is less. Fall plantings should be early enough to obtain adequate root growth to survive the winter. Spring sowings frequently are more satisfactory in the North, although good stands can be had in grain stubble in late summer and early fall.

Preirrigating the soil during seedbed preparation usually is advisable. It is especially important to fill the prospective root zone to field capacity on fine-textured soils that have slow infiltration rates. On a preirrigated field with different soils, the stands may be spotty if some parts dry rapidly.

Inoculated seed of an adapted variety should be drilled one-half inch or less in fine-textured soils and not more than 1 inch in sands and loamy sands. A firm seedbed and good contact between soil and seed provide moisture for germination, establishment of roots, and emergence as long as moisture remains in the surface soil. Contact of soil and seed in a cloddy seedbed may be inadequate unless irrigations are frequent or wet weather prevails. Drought kills more seedings than any other cause.

Irrigation after planting, for plant emergence, is unnecessary if the soil, climate, and seedbed preparation are satisfactory, but some growers prefer to plant in a dry seedbed, especially in sandy soils, to obtain an earlier planting date. Alfalfa planted in dry soil should be irrigated immediately. Additional irrigations may be necessary to soften any crust formation to permit seedling emergence. Frequent irrigations also may be necessary in sandy soils and in soils with appreciable salinity to prevent moisture stress from becoming detrimental to crop development. Irrigation after emergence is withheld if possible until the plants are 3 or 4 inches high or have 3 or more true leaves.

In many regions a companion crop of lightly seeded barley, wheat, or flax is advisable in anticipation of spring winds. Often alfalfa and the companion crop are seeded at the same time. When strong winds are expected,

alfalfa seed is drilled after the companion crop is about 6 inches tall so as to furnish protection against the action of wind and soil particles.

The main development of the alfalfa plant during the first few months is in the root system. Young seedlings are shallow-rooted and may suffer severely during warm weather and drying winds. The intervals between irrigations are increased as roots penetrate deeper into the soil.

Characteristics of crowns and roots may be changed under extremes of moisture—wilting and more than field capacity. Crown development is retarded and branching is limited if only the minimum of moisture is maintained after the plants emerge. Stressing the plant severely by withholding irrigation to attempt to force deep root penetration is not recommended. Very frequent irrigations, especially in compacted or fine-textured soils, affect aeration and may result in small crowns and a shallow branching root system, if not death. When the plant is young, anything that damages the growing root tips may cause a diversion from the typical taproot. With adequate moisture and aeration, seed inoculation results in good nodule distribution on the root system. Good rooting and inoculation increase the yield of hay, but early and frequent cuttings retard root development.

SALINITY, or accumulations of salt, retards the germination of seed, lowers the rate of growth, and lessens root penetration. The field should be leached before planting if the salt content is high. A salinity content giving a conductivity above 5 millimhos (a measure of electrical conductivity in proportion to salinity) in the saturation extract may retard germination. Roots can penetrate and function at less than 8 millimhos conductivity.

Soil moisture should be kept near field capacity while the plants are young. Frequent irrigations dilute the concentrated salt or remove it through leaching. A higher concentration of salt may be tolerated in fine-textured than in coarse-textured soils, because the former retains more water for dilution. If the root zone has good drainage, irrigation water containing appreciable salt (up to 8 millimhos conductivity) may be used without killing the crop. Excess water is added during winter to flush out accumulated salts if soil is too impermeable to permit leaching during the growing season.

Salinity is often associated with poor drainage, which may result in a high water table. When salt is present in the ground water in harmful quantities, it is advisable to keep the water table sufficiently deep so that the effect of the salt will not injure alfalfa roots within 4 feet of the surface.

MAINTENANCE of a satisfactory stand by good cultural practices is necessary for the best hay production. Conditions reducing plant vigor—extremes of moisture, salinity, nutrient deficiency, too frequent cuttings—leave the plant more susceptible to injury, disease, winterkilling, and the invasion of weeds.

Alfalfa uses large amounts of calcium, potassium, and phosphorus. The first two are abundant in most irrigated soils of the West. Supplemental phosphorus and perhaps boron are most frequently needed and are recommended for many soils. Appreciable uptake of either depends on adequate moisture.

Winterkilling, common in many States, is related to variety, plant vigor, soil moisture, and soil type. The high specific heat of water prevents less rapid temperature changes in wet soils than in dry soils. The greater dessication of crowns and roots in dry soil during freezing also is a contributing factor. Conversely, long periods of freezing and thawing on fine-textured, water-saturated soils heave, or lift, plants and expose crowns to harmful temperatures and dessication. The damage is less in soils with good surface drainage and underdrainage.

Alfalfa plants are injured if water

stands too long—24 to 48 hours—on a field, especially in hot weather. Dormant plants sometimes remain under water several days, however, without serious damage. Some growers believe that temperature is a dominant factor; they call the damage scalding. Scalding probably is caused by a combination of effects related to aeration and associated factors, such as nutrient uptake, assimilation, and respiration in the plant. The complicated injury seems related to oxygen deficiency, a carbon dioxide excess, and possibly the action of micro-organisms.

Alfalfa in fine-textured soils is more susceptible to damage from overirrigation than alfalfa on permeable, well-aerated sands. Poor soil structure, which may be worsened by irrigation, results in restricted air movement even after free water disappears. Bare areas in fields often indicate unsatisfactory localized drainage due to texture-structure relationships or may be associated with low spots that continually are overirrigated. They are usually the first places in the field to be overrun with weeds and grasses.

Yields usually suffer when the water table encroaches into the feeding zone of alfalfa. The severity of the damage for a given soil depends on depth to the water table. Answers to questionnaire by a number of soil, crop, and irrigation specialists in the 17 Western States indicate that the depths at which serious and little damage occurred were 29 and 38 inches, 40 and 51 inches, and 55 and 73 inches on sand, loam, and clay soils, respectively. If appreciable salinity exists, there should be 1 to 3 feet more root zone above the water table. A fluctuating water table is dangerous if an appreciable part of the root system is submerged for an extended period during the growing season. The minimum permissible depth to a fluctuating water table is considered 42, 58, and 72 inches for sand, loam, and clay soils, respectively. Proper irrigation often prevents the establishment and rise of a ground water table to a dangerous level.

Irrigation of alfalfa often receives a lower priority than irrigation of other crops because alfalfa will maintain itself over a wide range of moisture conditions. Since foliage of the alfalfa plant is the part harvested, rapid growth should be promoted. Production is increased by yearly total water applications in excess of those needed for the maximum yield of most other crops.

Wet soils warm up more slowly than dry soils. The first irrigation in the spring should be delayed until the soil is warm enough for active growth. The cooling effect of water is utilized to advantage in midsummer in hot regions of the Southwest. It is believed that frequent irrigations produce a more favorable environment for growth of plant roots, especially in the surface foot of soil.

It is considered good practice to irrigate as late as possible before cutting to supply sufficient moisture for rapid growth of new stems and leaves after the cutting. The irrigation before cutting should be early enough to permit the surface soil to dry sufficiently so that harmful compaction by harvesting equipment is avoided.

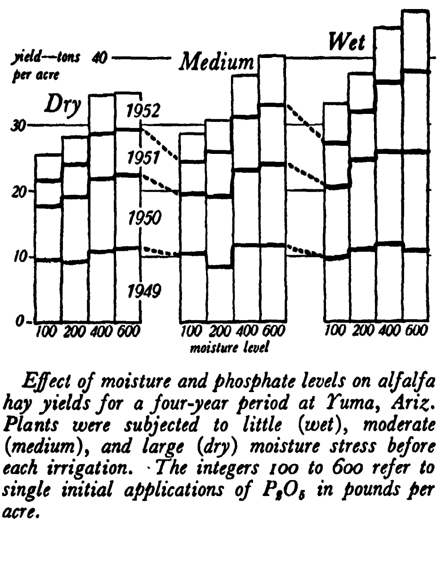
Plants a year old can withstand considerable drought. On some impermeable soils alfalfa commonly is forced into summer dormancy during July and August to prevent scalding and to control weeds. Even on well-drained soils of the Southwest, the rate of growth is retarded in late July and all of August. Irrigation then favors growth of summer weeds and grasses in the moist surface soil.

The amount of available water in the root zone of soils with low infiltration rates may decline gradually during the growing season despite regular irrigation. If so, an additional irrigation may be advisable after the last hay cutting in the fall to recharge the root zone reservoir.

In cooler climates, alfalfa production remains substantially unchanged over a range of irrigation management. Maximum growth, however, ceases

sometime before wilting starts. Moisture stress, indicated by a bluish-green color of foliage, develops before severe wilting. It is perhaps most critical in sandy soils and in hot climates, where the limited capacity to store moisture and the high daily water use provide a small safety factor between evidence of stress and severe damage.

At Yuma, Ariz., different moisture tensions at various phosphate levels affected yields, as shown in the accompanying chart. Moisture stress and frequency of irrigation appear to have more of an effect on hay production than on maintenance of the stand.



Effect of moisture and phosphate levels on alfalfa hay yields for a four-year period at Yuma, Ariz. Plants were subjected to little (wet), moderate (medium), and large (dry) moisture stress before each irrigation. The integers 100 to 600 refer to single initial applications of P_2O_5 in pounds per acre.

Consumptive use of water means the water used by the plant plus the water evaporated from the soil in which the crop is growing. The need of alfalfa for water depends on the age and vigor of the plants, availability of nutrients, depth and texture of the soil, topography, infiltration rate, method of applying the water, moisture stress, depth to ground water, rainfall, temperature, wind movement, daylight hours, wind velocity, length of growing season, presence of salt in the profile, and rate of intake of water. Other things being equal, more frequent irrigations are needed in warmer sections of the South than in the cooler sections of the North.

With adequate moisture, suitable soil, and a good stand, the most important factors affecting consumptive use by alfalfa are length of growing season and temperature. Total use of water is proportional to the length of the growing season. Peak use occurs in summer. Because length of growing season and temperature are associated, an estimate of seasonal consumptive use may be obtained if the length of growing season is known for a given location. Data from 11 States were analyzed for 31 measured determinations of consumptive use. Some values represented average results for several years at a given location. The analysis of data ($r=0.956$) indicates an average consumptive use of 0.23 acre-inch a day for the growing season without regard for location.

From results of experimental studies on alfalfa throughout the Western States, the Blaney-Criddle index was developed. By its use, the consumptive use of water is estimated from the mean monthly temperature, length of growing season, and daytime hours. As the necessary climatic data are readily available, consumptive use may be calculated for most sections of the West.

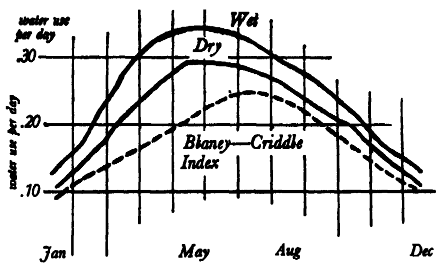
The more frequently land is irrigated the greater the evaporation loss from the soil—a part of the consumptive-use figure. When fields are irrigated at varying degrees of dryness, in addition to the increased evaporation loss from the soil, more water is transpired by the plant at low moisture stress (wet) than at high stress (dry).

That is shown in the accompanying chart from an experiment conducted at Yuma, Ariz. Both the daily rate of water use and the total yearly use were greater for the wet, or low-stress treatment. At Prosser, Wash., S. J. Mech irrigated when 50, 35, and 15 percent of the available water was retained in the soil. The consumptive use of water for the year was 42, 36, and 33 inches, respectively.

When the application of phosphate

fertilizer increases yields of hay, the consumptive use of water also increases. The increased use of water, however, is not proportional to the greater yields. Water is used more efficiently as phosphate is increased to meet crop needs.

The daily rate of consumptive use of water by alfalfa is affected by stage of development of the plant. Cutting and removal of the crop sharply reduces the amount of water used. Transpiration again increases as growth develops, and the use of water levels off when a reasonable foliage cover is reestablished.



Consumptive use of water by alfalfa during the year at Yuma, Ariz., as affected by moisture stress. Plants were subjected to little (wet) and appreciable (dry) stress before each irrigation for a 3-year period.

Consumptive use may vary more than 100 percent in alfalfa-producing areas of a given State. For instance, the calculated consumptive use of water in areas of Nevada varies from 14 to 56 inches. A minimum consumptive use for alfalfa in the Western States, 12 to 16 inches, was calculated for alfalfa produced in mountain valleys, where growing seasons are short. The maximum was a measured value of 88 inches on the Yuma Desert in Arizona. The highest average monthly water use in this case was during May and June, an average value of 0.34 inch daily. With high temperatures, low humidity, and appreciable wind, the daily peak consumptive use exceeded 0.5 inch. K. Harris and W. D. Criddle estimated that the peak daily use of water for alfalfa is about 0.20 inch a day in a cool climate, 0.25 inch in a moderate climate, and 0.30 inch in a hot climate, such as in the Imperial Valley of California.

When and how much to irrigate depends on the rate alfalfa uses moisture and the capacity of the root zone for available water. The Blaney-Criddle index gives a usable estimate of the rate of water use by the plant for a given location. Daily use should be considered, because it varies from essentially zero in the spring to 0.2 inch or more a day in midsummer, depending on conditions and location. A careful estimate of the maximum available moisture in the root zone of a particular soil supplies the other needed information.

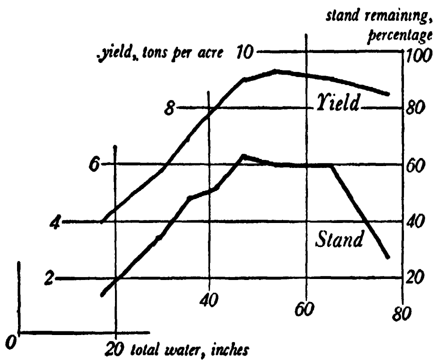
A survey concerning irrigation schedules indicates that 60 percent of the alfalfa growers irrigate after each cutting, 25 percent when water is delivered, 10 percent on plant appearance, and 5 percent from soil examination.

It is not possible to delay irrigation until the plant roots extract all the available water from the root zone. Although abundant available moisture is present in the deeper root zone, yields may be reduced by moisture stress because insufficient roots are present to absorb necessary amounts of water. Available moisture in the root zone reservoir should be replenished before the rate of growth of the plant is lowered appreciably.

Because adequate moisture and aeration are necessary, best growth is expected when 35 to 85 percent of the readily available moisture remains in the active root zone. The variable texture and depth of soils, however, mean greatly different capacities for available moisture. It is simpler to schedule irrigations when a certain amount—2 or 3 inches of available water—remains in the active root zone than when 35 percent remains. When the moisture-holding capacity of the root zone and the daily moisture use are known, the irrigation date may be calculated. The available moisture retained provides a

safety factor for miscalculations, delayed water delivery, and insufficient roots in the lower extraction zone.

HOW MUCH WATER should be applied depends on the depth of the active root zone and the amount of available water it will hold. The depth of the active root zone is determined by sampling the soil twice. The first samples are taken 2 or 3 days after a thorough irrigation, and the moisture is determined to a depth of several feet. Subsequent irrigation is withheld until the leaves turn bluish green—the indication of moisture stress. Then the soil moisture content is determined again. Moisture loss in the various horizons defines the active root zone.



Effect of amount of water—annual applications plus precipitation—at Davis, Calif., on 6-year average yields and final stand counts of alfalfa.

Available moisture in most soils varies from 0.7 to 2.0 acre-inches to the foot, depending on texture. A sand or loamy sand retains less than 1 inch of available water a foot of soil, but moisture in fine-textured soils may exceed 2 inches. Laboratory analyses provide more precise estimates.

Irrigation must provide enough water to supply the consumptive-use requirements of alfalfa plus an additional amount to satisfy deep percolation and runoff losses. Maximum efficiency of irrigation is obtained by refilling only the root zone reservoir, unless the presence of salinity requires some leaching.

More than 90 percent of total water extracted from the soil in many irrigated areas comes from the upper 3 feet if alfalfa depends on surface irrigation. The upper 6 feet include the major moisture removal zone of alfalfa unless ground water is important. As a rule, little increase in yield is realized by applying more than 6 inches of water at a single irrigation, regardless of soil type. A 6-inch irrigation is a heavy one and is justified only on deep, well-drained, medium-textured soils, well permeated with roots. Applications of 3 or 4 inches may be enough.

Shallow, sandy, or saline soils may require twice as many irrigations as a fine-textured soil. On comparable soils and elevations, the number of irrigations increases with the longer growing season farther south. Three or fewer irrigations may be used for 2 or 3 cuttings in the Dakotas; more than 20 may be needed on sandy or saline soils in the Southwest for 7 or 8 cuttings.

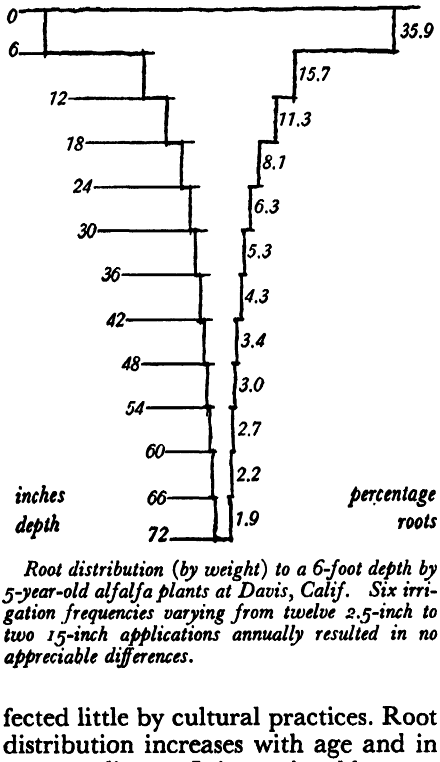
The time necessary to apply efficiently the desired amount of water depends on the rate the soil will absorb moisture—that is, the infiltration rate. Sands, loams, and clays usually have fast, medium, and slow infiltration rates, respectively. The alfalfa plant itself increases the infiltration rate of a soil. At Prosser, Wash., second-year alfalfa increased infiltration 69 percent and 138 percent the third year.

Good yields of hay sometimes are had when moisture comes from a water table 10 feet or more below the surface. Root development is extensive in the horizon containing moisture just above the water table. One can conclude, therefore, that frequent irrigations are not mandatory if roots penetrate to the capillary fringe above a water table and nutrients are adequate.

Irrigation is supplemental to rainfall in a few Western States. Only a single irrigation in a year may be required there. The yearly fluctuations in amount and frequency of rain are taken into account in scheduling irrigations. Where soils are deep, large amounts are stored for later use.

The moisture extraction pattern is an indicator of root activity. The zone of moisture extraction is roughly proportional to the distribution of the alfalfa roots.

The root system is characterized by a taproot, which may penetrate more than 20 feet into deep, well-drained soils. Small rootlets provide much absorbing surface for moisture and nutrients. Root distribution normally is affected little by cultural practices. Root distribution increases with age and in a warm climate. It is restricted by poor aeration, a high water table, impervious layers, destructive organisms, and salinity. Roots may concentrate abnormally in the vicinity of needed fertilizer, textural layers, and in the moist zone above a water table.



Root distribution (by weight) to a 6-foot depth by 5-year-old alfalfa plants at Davis, Calif. Six irrigation frequencies varying from twelve 2.5-inch to two 15-inch applications annually resulted in no appreciable differences.

The three principal factors affecting the moisture extraction pattern are extent and distribution of roots, water availability and distribution, and root vigor and factors affecting it. The largest amount of water normally is used from the surface. Progressively smaller amounts come from deeper zones in the profile. The alfalfa plant will draw a major part of its moisture, if available, from the top 4 feet in most irrigated soils. Moisture held at the same tension throughout the root zone is removed proportional to root distribution. If stress varies greatly, however, more water may be removed from the zone of small tensions.

Small variations in moisture between wilting and field capacity have little effect on the rooting habits of alfalfa. In two places in California, a total of 30 or 36 inches of irrigation water was applied annually to establish and grow alfalfa. The total water for each year was applied in 2 to 12 applications. At the end of 3 to 5 years, excavation and root removal to 6 feet revealed that depth of application or frequency of irrigation had no effect upon the distribution of roots.

A basic pattern of moisture extraction was proposed by D. R. Shockley in 1953. From available data for a number of crops, Dr. Shockley concluded that most irrigated crops have similar moisture extraction patterns. Although depth of rooting varies, about 40 percent of the extracted moisture comes from the upper quarter of the root zone, with 30, 20, and 10 percent for successive quarters. Recently I analyzed data from 28 alfalfa tests conducted in 10 States. Average results were 47, 26, 17, and 10 percent for the four quarters, but variations among locations were large.

Alfalfa grown for 4 years on deep, fine sand at Yuma, Ariz., was irrigated at different levels of moisture stress in the root zone. Alfalfa irrigated frequently ("wet," or little moisture stress) utilized 27 percent of the available moisture from the surface 4 feet of soil between irrigations. Tensiometer readings taken before irrigation indicated that roots were most active in removing water at the 6-inch depth. Eighty-five percent of the total water used came from the surface 4 feet of soil.

Alfalfa irrigated infrequently ("dry,"

or appreciable moisture stress) used 80 percent of the available moisture to 48 inches. The most active root zone was from 24 to 36 inches deep. Seventy-two percent of the total water used came from the surface 4 feet of soil.

Activity of feeder roots near the soil surface is reduced in some regions during hot weather. Frequent irrigations at Yuma result in increased water extraction from the surface foot of soil, apparently through a cooling effect.

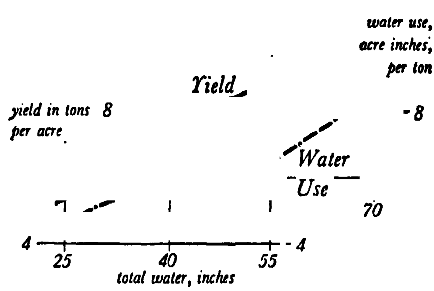
Supplemental phosphate, necessary for hay production on the Yuma Mesa, also influences the zone of moisture extraction. Phosphorus movement in soil was found to be proportional to the amount applied. Large applications increased the relative activity of roots, apparently by penetrating to where phosphorus could be reached by roots, notwithstanding high soil temperature conditions adverse to plant growth. Thus the rooting habit of the plant was altered to take advantage of a condition otherwise limiting growth.

Another factor influencing the zone of moisture extraction is the sloughing of rootlets during the summer. This deterioration begins in late spring. There is little regrowth of the rootlets until cool weather returns.

Water utilization efficiency indicates the water transpired and evaporated from the soil per unit of dry matter produced. It can be expressed as acre-inches or acre-feet of water used to produce a ton of hay.

The efficiency of water utilization depends on the growth and transpiration of alfalfa. Growth and transpiration are related to plant vigor and such environmental factors as climate, soil productivity, and soil moisture stress. Climate is the most important. Factors influencing the evaporative power of the aerial environment are principally involved. If growing conditions are satisfactory, the transpiration rate of the plant increases with increasing temperature, decreasing relative humidity, and greater wind movement.

The minimum requirement for alfalfa in the Dakotas appears to be about 4 acre-inches per ton of hay produced; while the minimum in the warmer climate of southern portions of California or Arizona is in the range of 6 to 8 acre-inches.



Alfalfa yields and water utilization efficiency at Delhi, Calif., as affected by total amount of water available annually for hay production during a 3-year period.

Alfalfa growth and transpiration appear interdependent until a large leaf area has developed and a satisfactory rate of tissue production is reached. Beyond that point, however, the transpiration rate varies appreciably, with little effect on the growth. At Riverside, Calif., wide, consistent differences in the water requirement occur during the year. Only 57 percent as much water was used in producing a ton of hay in the spring and early summer as that required in late summer and fall. Results from a 4-year study at Yuma demonstrate the same trend. The water requirement increased gradually from March to mid-July. Fifty-three percent more water was required per ton of hay for the month of July 15 to August 15 than for the month June 15 to July 15. The climatic conditions were not sufficiently different between the two periods to account for this large difference in water requirement. The rate of growth, however, was unsatisfactory. Evidence at Yuma indicates the water utilization efficiency is less not only for the excessively hot period of summer but also during weather too cool for good growth.

Alfalfa growing on highly productive soils utilizes water more efficiently than alfalfa grown in infertile soils that have poor aeration and harmful salinity concentrations. Increasing alfalfa growth by improving the productivity of a soil results in the transpiration of a larger total amount of water. Water utilization efficiency is greater, however, for larger yields are obtained without any proportional increase in water transpired. In the study at Yuma, 14 acre-inches of water were required for a ton of hay on soil deficient in phosphorus. For the same soil receiving adequate phosphate, 8 acre-inches were required.

Under severe moisture stress, the plant makes little or no growth, yet continues to use some water. At the other extreme, if soil is too wet, transpiration by the plant and evaporation from the soil surface are increased. The effect of stress is more pronounced on growth than on the use of water per ton of hay produced. Variation in soil moisture within the available range apparently has no important effect on the water utilization efficiency until extremes are approached.

THE MOST IMPORTANT PROBLEM in much of the irrigated West is that of getting maximum economic production from limited water supplies. In such areas farmers are now growing crops requiring a minimum of water for maximum cash return. Some of the wide variations mentioned in amounts of water necessary to grow alfalfa are controllable under good cultural management.

Emphasis should be given to increasing the efficiency of water utilization to permit the farmer to grow the crop he chooses. Increasing the efficiency of water utilization for alfalfa is the last phase of the process that begins with the delivery of water to the farmer's headgate. As research provides more information and as the need for water becomes greater, it should be possible to sustain alfalfa production at the 1955 level with little more than half the water used for it.

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Since alfalfa is produced under diverse conditions in widely separated locations, a questionnaire was sent to a number of soil, irrigation, and crop specialists in the 17 Western States. The author appreciates the help given by these persons: T. S. Aasheim, D. C. Aepli, M. Amemiya, W. C. Barrett, L. Bernstein, F. A. Chisholm, N. R. Crawford, W. D. Criddle, H. E. Dregne, L. V. Doneen, L. J. Erie, L. O. Fine, R. M. Hagen, E. C. Hanson, A. J. Hazen, G. B. Hoff, C. E. Houston, O. W. Howe, M. R. Huberty, F. E. Koehler, C. A. Larson, W. E. Larson, R. W. Leamer, P. J. Lyerly, J. Q. Lynd, A. W. Marsh, S. J. Mech, W. R. Meyer, V. I. Meyers, C. H. Pair, A. H. Post, R. B. Powers, R. E. Ramig, D. W. Robertson, E. P. Ross, O. F. Smith, B. R. Somerhalder, N. P. Swanson, F. M. Tileston, R. S. Whitney, F. M. Willhite, M. L. Wilson, and G. O. Woodward.

The very earth of our country is gradually getting lost to us. One-third of the fertile top layer of our soil has already been washed away into rivers and the sea. This must be stopped, or some day our country will be too barren to yield us a living. This is one national problem crying for solution; it affects you directly and decisively!

—DWIGHT D. EISENHOWER

Development and Improvement of Coastal Marsh Ranges

Robert E. Williams

The coastal marsh belt, which extends from the southern tip of Texas to Florida, contains millions of acres of grazing lands. The belt is only a few hundred feet wide in some States. It is more than 50 miles wide in the Mississippi River Delta areas south of New Orleans. Its elevation ranges from 2 feet below sea level to 2 feet above sea level. The largest and most important range areas are in southwestern Louisiana and southeastern Texas. Louisiana alone has 2 million acres of marsh grazing lands.

The climate is subtropical. The rainfall averages 40 to 60 inches annually. The temperatures range from 20° to 102° F. The marshes are inundated periodically by a flow of fresh water from the highlands or by wind tides, which pile up waters from the Gulf of Mexico. The marshes are famous as fur-producing and waterfowl-wintering areas, but little has been written about the production of livestock on their areas that have mineral and organic soils that are firm enough to support cattle.

The water problems in the marsh are involved. Periods of flooding may follow periods of drought severe enough to curtail plant growth. Fluctuations in the quality of water are just as complex. Fresh water from high land may be replaced in a short time with salt water drained in from the gulf through channels and canals.

Low coastal ridges, or cheniers, transect the marsh in southwestern Louisiana from east to west nearly parallel to the present beach of the Gulf of Mexico. These narrow ridges are old beaches and are a few inches to 5 or 6 feet above general marsh elevations.

The larger cheniers were originally covered with liveoaks and other hardwoods. Settlers began to locate along these ridges early in the 19th century. They cut much of the timber for their cabins, fences, firewood, and for smokewood, which they burned during the mosquito seasons.

The soils of the cheniers are mineral and include clays and loamy fine sands, with frequent deposits of seashell. The soils are fertile, but the cheniers were too small to support the growing numbers of people. More and more they turned to the marsh itself to earn a livelihood from cattle, hogs, and trapping.

The marshes were practically limitless, unfenced, and produced an abundance of nutritious grasses for livestock. Cattle roamed at will when the marshes were dry and along the ridges when water covered almost all of the country.

Hazards in cattle operations in the marsh area are heat, insects, disease, heavy rainfall, wind tides that submerge grazing areas, lack of shelter, prolonged droughts, and unstable soils, where cattle bog. Additional problems are overgrazing, poor distribution of grazing, lack of fences, inadequate water fit for livestock to drink, uncontrolled marsh fires, intrusion of salt water, too many undesirable plants, and lack of reserve feed supplies for critical periods.

Livestock numbers have continued to increase despite numerous local hardships. Through natural selection, as much as through planned improvement, a strain of crossbred cattle has been developed that endure heat, withstand insects, and, when necessary, graze belly deep in water.

Soil conservation districts in southern Louisiana in 1948 became aware of marsh conservation problems and began planning for their solution. The districts gave the landowners help in planning and applying conservation measures on the ranges where natural soil and water conditions make native forage plants the most valuable crop from the land.

FRESH-MARSH RANGE and salt-marsh range are the two range sites in the marsh area. A range site is an area sufficiently uniform in soil, climate, and natural biotic conditions to produce a particular climax vegetation—the culmination stage of the possible development of vegetation in a region. Fresh-marsh range has vegetation that grows only under practically fresh-water conditions. It extends along the inland side of the marshes where fresh water from prairies and bottomland accumulates.

The salt-marsh site covers the broad band that extends from fresh-water conditions to the gulf. Some mixing of plants occurs in these broad sites, but each site can be readily recognized by the presence of the key plants that distinguish it.

Range condition is determined by summarizing the climax and other vegetation on each site. Areas are classified into excellent, good, fair, and poor conditions, according to the kinds of plants present. Range conditions show how far the range has deteriorated below its potential producing capacity. Range conditions are helpful guides in adjusting range use and selecting practices that will maintain excellent and good conditions or improve fair and poor conditions.

Paille fine (*Panicum hemitomon*), giant-cutgrass (*Zizaniopsis miliacea*), and common reed (*Phragmites communis*) are the most nutritious plants in fresh marsh and are the key plants in determining range condition. The three grasses decline under heavy grazing because livestock eat them first. They are green all year when winters are mild. They make up 75 to 100 percent of the vegetation on fresh-marsh ranges in excellent condition, 50 to 75 percent on ranges in good condition, 25 to 50 percent on ranges in fair condition, and 0 to 25 percent on ranges in poor condition.

Paille fine is killed above the ground by frost. Giant-cutgrass and common reed, less vulnerable to freezing, furnish good winter grazing almost every year. Giant-cutgrass is an indication of firm soil conditions. Paille fine grows under soil conditions varying from firm mineral clays to "floating" organic marsh. Common reed grows on both fresh- and salt-marsh range.

Smartweeds (*Polygonom* species), alligatorweed (*Alternanthera philoxeroides*), rattlebox (*Daubontonia drummondi*), and other weedy plants invade fresh-marsh range when the better grasses are grazed out. Productivity of poor and fair condition range is only half that of ranges in good and excellent condition.

Range in excellent condition will carry one animal unit on 3 acres. Range in good condition carries one animal unit to 4 acres; fair range carries one animal unit to 6 acres; and poor range can take care of one animal unit to 10 acres.

Salt-marsh forage grasses of highest value are marshhay cordgrass (*Spartina patens*), big cordgrass (*Spartina cynosuroides*), smooth cordgrass (*Spartina alterniflora*), seashore saltgrass (*Distichlis spicata*), and common reed. Range condition is best where most of the cover is composed of those grasses. Seashore paspalum (*Paspalum vaginatum*) and longtom (*Paspalum lividum*), two crawling grasses of good forage value, increase on some types of salt-marsh range in the early stages of overgrazing. Longtom is valuable for hay production and as a tame pasture plant. It grows from slightly salty areas to strictly fresh sites. Needlegrass rush (*Juncus roemerianus*) and bigleaf sumpweed (*Iva frutescens*) are the principal invaders in salt-marsh range in low conditions.

Olney bulrush (*Scirpus olneyi*) and saltmarsh bulrush (*Scirpus robustus*) are also found on salt-marsh range. They are eaten by cattle, but their greatest value is as food for muskrats. On areas high in muskrat production, grazing management often is planned to favor those two plants.

Hairypod cowpea (*Vigna repens*) is the most common legume in the marsh. It is found on slightly elevated areas in

both range sites. Being an annual, it is not very dependable for grazing. In favorable seasons it makes a large volume of forage, which is readily eaten by cattle.

Salt-marsh range in excellent condition will carry one animal unit to 4 acres; good condition, an animal unit to 6 acres; fair condition, an animal unit to 8 acres; and poor condition, an animal unit to 12 acres.

The number and distribution of the low coastal ridges in marsh range has a profound influence on distribution of livestock grazing. Cattle stay on or near the ridges when water covers the marsh. They serve as places for the cattle to rest and leave young calves while grazing. Here they get some relief from mosquitoes. Ridges are the only places where cattle can be cared for and fed during times of emergency.

Ridges and adjacent areas are usually severely overused; more distant range is properly used; and remote areas may be used too little or not at all. During prolonged wet seasons, many ridges are denuded by concentrations of cattle even when the range unit as a whole is properly stocked.

UNIFORM RANGE USE is achieved by many stockmen by the construction of cattle walkways—earthen levees constructed from ridges into range areas to improve accessibility and encourage uniform use. They serve as trails, bedground, calving locations, and a resting place for young calves while the mothers graze. They enable the live-

Analysis of Several Marsh Range Forage Plants

Plant	*Growth stage*	*Percentage of crude protein*	*Percentage of phosphorus*	*Percentage of calcium*
Paille fine	young	18.31	0.21	0.19
(*Panicum hemitomon*)	bloom	16.75	.19	.60
	mature	....	....	....
	dormant	9.42	.08	.18
Giant-cutgrass	young	15.50	.18	.58
(*Zizaniopsis miliacea*)	bloom	13.94	.17	.75
	mature	12.00	.16	.78
	dormant	6.00	.08	.48
Common reed	young	17.16	.22	.21
(*Phragmites communis*)	bloom	13.86	.15	.37
	mature	....	....	....
	dormant	11.31	.09	.16
Longtom	young	13.11	.23	.34
(*Paspalum lividum*)	bloom	10.25	.17	.57
	mature	....	....	....
	dormant	6.56	.12	.50
Marshhay cordgrass	young	12.74	.17	.17
(*Spartina patens*)	bloom	7.50	.10	.22
	mature	5.42	.10	.26
	dormant	....	....	....
Big cordgrass	young	12.33	.22	.18
(*Spartina cynosuroides*)	bloom	6.16	.15	.49
	mature	6.56	.12	.60
	dormant	5.19	.09	.27
Smooth cordgrass	young	11.09	.20	.35
(*Spartina alterniflora*)	bloom	7.81	.17	.53
	mature	9.50	.17	.74
	dormant	....	....	....

Analyses were made by Regional Operations Laboratory, Soil Conservation Service, Fort Worth, Tex., in 1950. Samples were collected monthly during 1950.

stock operator to work his cattle at any season of the year.

Borrow-pits, from which earth is taken to build the walkways, are staggered from side to side of the levee at intervals of several hundred feet. Cattle thus can move off the levee to graze from either side. Staggered pits also prevent the flow of water off the range. When the walkways are built along a range boundary, the earth can be taken from the boundary side of the levee. Plugs of earth are left in the pits at intervals to prevent the flow of water. Walkway pits along range boundaries are effective firebreaks to help in the control of marsh fires.

Bridges or culverts are provided whenever the walkways cross natural drainages. By staggering pits or leaving the plugs in boundary pits and installing bridges, interference with natural water conditions is kept to a minimum. Range growth is not materially altered by properly constructed walkways.

Soundly constructed walkways are built at least 2 feet high above average high-water levels and should be 10 feet wide. They usually are connected to existing ridges, canal levees, or other embankments. Cattle will graze about a quarter of a mile from a levee when water is on the marsh. Walkways therefore are spaced about one-half mile apart.

Oil companies build many roads in marsh ranges to their wells. Ranchers who know the value of walkways are asking oil companies to stagger borrow pits or plug them along roads constructed on their property. The roads then serve as satisfactory walkways.

Walkways seem to improve wildlife habitat. The pits create open water areas, which are used by some types of waterfowl. They create an average of 2.5 acres of open water area per mile of walkway. Mottled ducks nest along walkway pits in range areas that are rested from grazing during summer months. Mink and otter have been seen along the levees. Where walkways have been built on range land that produces muskrats, landowners believe that the cattle do less damage than usual to muskrat mounds. Young calves often bed on the mounds but prefer the firmer and more accessible walkways when they are available.

Walkways constructed in Louisiana marsh range between January 1, 1950, and January 1, 1955, total 60 miles. They were made by draglines operating on mats. The average cost has been 1,300 dollars a mile, not including the expense of bridges. Reduced death losses and improved calf crops on ranges served by walkways make the practice popular with ranchers.

FENCING is increasing on many marsh ranges. Fences control the movement of cattle, defer range use, and permit use of better bulls.

Two neighboring cattlemen in Cameron Parish, La., constructed a double-size, partnership walkway along their boundary line with a good fence down the middle. The large walkway has staggered pits so each man gets full use of his range. The fence enables the men to control their cattle numbers and season of use and to use other good management practices.

Other ranchers have cross-fenced their range to practice rotation grazing. The most important benefit from fencing is improvement in range vegetation, because cattle numbers can be controlled and some pastures can be rested while others are grazed.

Livestock watering facilities are needed on many ranges. Water in bayous, ponds, and pits often becomes too salty in summer for cattle to drink. Fresh water from wells is the most dependable kind for livestock to use. Deep ponds on ridges are successful in places where soil conditions favor construction. Availability of fresh water in borrow pits along walkways helps to keep cattle from overusing areas around permanent water during the spring months. Water in borrow pits, however, may become unfit for animals in long dry periods.

Burning has been practiced widely in marsh areas. Stockmen and trappers

burn off the heavy cover of mature marsh vegetation to stimulate new, succulent growth for both cattle and wildlife and to increase the availability of forage. Vegetation is severely damaged by burns in periods of drought, when fire can reach plant crowns and roots.

Uniform grazing, walkway pits, and canals are all useful in controlling unplanned or accidental burns.

Cattlemen attempt to burn the same area only every other year at a time when the ground surface is covered with water. Research on the effects of burning on individual plant species, forage value, and forage volume is greatly needed.

INTRUSION of salt water from the gulf into the marsh area through rivers, bayous, and drainage and transportation canals occurs periodically in many areas. A marsh that is classified as salt-marsh range can be greatly damaged by water with heavier concentrations of salt. In drought periods when the movement of fresh water to the gulf is severely reduced, salt water sometimes flows up the drainages and canals. Heavy south winds blow salt water inland for a considerable distance, causing it to spread over marsh-range areas along the drainages. Salt water sometimes fills fresh-water lakes during periods of wind tides and when water levels in the lakes are low. As the water evaporates, salt concentrations become greater, to the extent that soils and vegetation are damaged and various forms of aquatic wildlife habitats may be destroyed.

Soil that is saturated with fresh water before the salt water comes in is not usually damaged. Heavy soil that is dry when salt water comes in absorbs considerable salt when the water recedes. Such salting kills the less salt-tolerant plants and causes fine-textured mineral and organic soils to become soupy. Productivity of such areas is greatly reduced, and they may actually become hazardous to livestock.

The problem has been met in a few instances by the construction of gates in drainages to prevent inflow of salt water. The gates are closed during dry periods when there is a danger of intrusion of salt water. The gates are left open during favorable seasons to permit natural water movements. The use of gates to protect range areas from salt water intrusion needs to be increased.

Planting of salt-tolerant plants on salted areas has been practiced on a small scale. Smooth cordgrass was planted successfully in a salted area south of Grand Chenier, La. If salting of an area takes place gradually over a number of years, changes in plants may take place naturally.

Additional studies are needed to determine the dangers of salt-water intrusion to soils, vegetation, and wildlife throughout the marsh area. The problem becomes more critical as natural marsh communities are disturbed by dredging of ship channels and the construction of roads, canals, and industrial developments.

SUPPLEMENTAL FEEDING or improved pastures are necessary on most marsh ranges to provide an adequate yearlong forage supply. Paille fine marshes produce little green forage during cold weather. Forage left from the growing season weathers rapidly and soon becomes unsatisfactory for feed. Unless warm weather brings new growth, cattle must be moved to winter time pastures on high land or must be fed hay and concentrates on the range. Supplemental feeding too often is delayed until cattle have lost considerable weight.

Where giant-cutgrass and common reed make up a large percentage of the fresh-marsh vegetation, forage quality usually holds up better during the winter, but some feeding is desirable in critical periods. Balanced mineral supplement should be fed on fresh-marsh yearlong.

Salt-marsh ranges hold cattle weights up well during winter months except during prolonged droughts, severe storms, or freezing weather. Mosqui-

toes force the movement of cattle from a large part of salt-marsh range country in summer. The average grazing period for salt-marsh range is mid-October until mid-April. Most summer grazing is provided by fresh-marsh range and improved pastures on the cheniers. Some large herds are trailed to the prairie area north of the marsh to graze improved pastures or idle rice-land. Several successful cattle operations are based on the use of marsh range for 6 months in winter and cut-over longleaf pine range for 6 months during the warm season. The herds are trailed—sometimes as far as 70 miles—or trucked between the range areas each October and April.

Small fields are sometimes enclosed by protection levees, and the excess water is pumped out. They are used for hay production and pasture for extra forage during critical periods. They may be an important part of an overall livestock operation on the marsh.

The use of improved tame pasture in combination with marsh range forage has been increasing. In winter the tame pasture is composed of oats, ryegrass, fescue, and clovers. Summer tame-pasture plants are bermudagrass, dallisgrass, longtom, rhodesgrass, and lespedeza. Hay is cut from improved pastures during periods of peak growth. Alyce-clover and lespedeza are the two most commonly used legumes for straight hay production. Some operators feed cottonseed cake, meal, and range cubes. Greater use of feed and concentrates on the range during critical periods undoubtedly would increase overall production.

THE CONTROL of undesirable vegetation is being practiced in a few localities in marsh areas and on ridges. Airplane spraying with chemical mixtures is used to control rattlebox and sesbania, two weedy legumes. Stockmen have had nearly 10,000 acres of marsh sprayed since 1952 for control of these weeds at a total cost of approximately 2 dollars an acre. Conventional and shredding mowers are used to control annual weeds, small brush, and coarse grass on ridges. Management that favors the better forage plants is the best overall weed control.

THE DEVELOPMENT and improvement of coastal marsh ranges depends on the maintenance of natural soil and water conditions and increasing the better forage plants through livestock management. As marsh livestock men apply these principles of management, productivity of their ranges will increase. Biologists and landowners interested in both cattle and wildlife generally agree that the management practices that maintain high range conditions or improve low conditions are beneficial to fur-bearers as well as to cattle. The marsh range area is small in total area as compared to western range areas, but it is an important part of the economy of the local people, States, and the Nation. Properly improved and developed, production from marsh ranges can be greatly increased.

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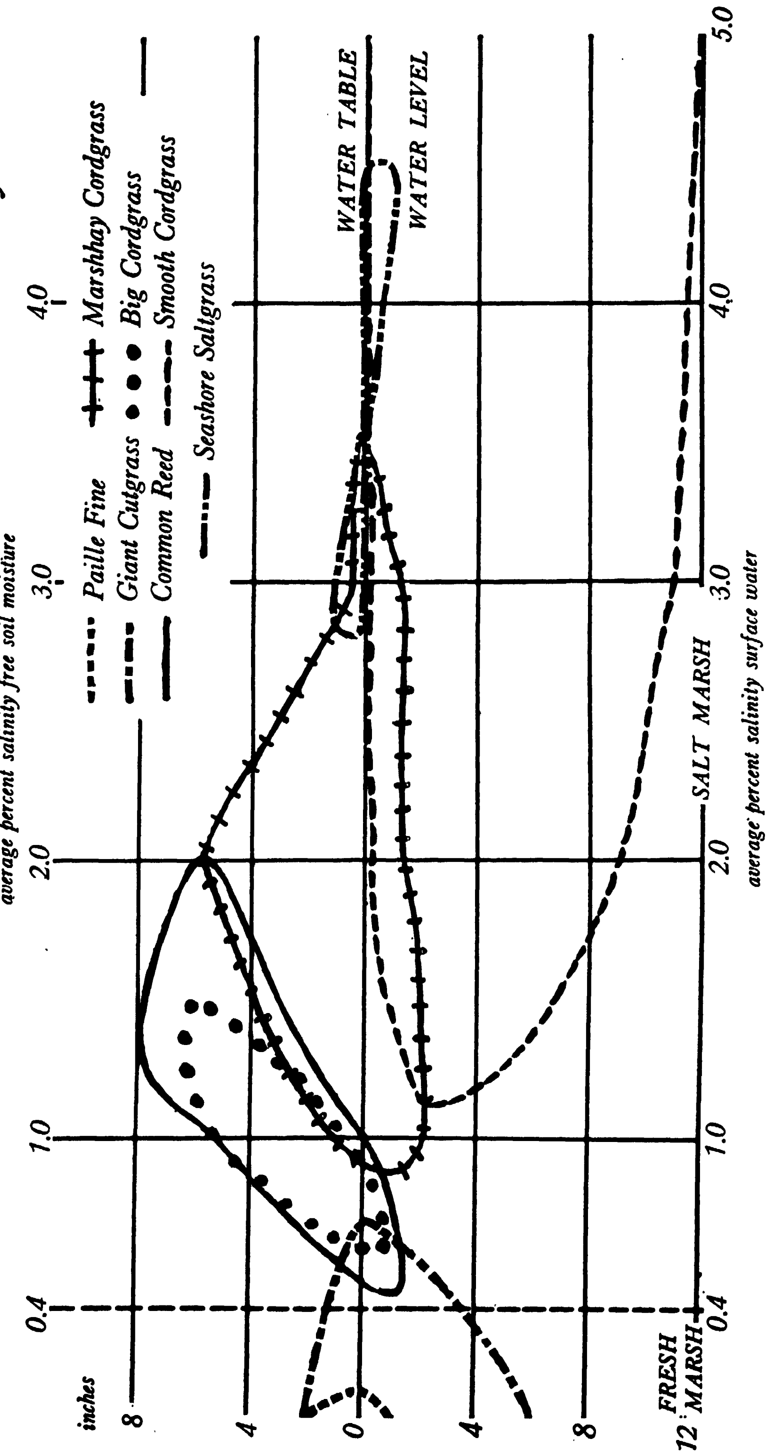

Approximate Ranges of Species Dominance in Relation to Water and Salinity

Gardens, Turf, and Orchards

The Proper Use of Water in the Home Garden

Victor R. Boswell and Marlowe D. Thorne

Amateur and home gardeners in the so-called humid parts of the United States generally do not appreciate that suitable irrigation often can be profitable or that most districts definitely need some irrigation nearly every year. In the dry parts of the West, however, irrigation requirements and practices generally are as well understood by the amateur gardener as are other essential garden operations, such as plowing or spading, planting, and cultivating.

Nearly all vegetables require relatively large amounts of water for their profitable production, and in all regions of the country there are almost certain to be some periods in every growing season when rainfall will not be sufficient to produce best results.

The frequency and duration of dry periods and the net increase in value of the crop which can be produced by irrigation during such periods determine the advisability of irrigating vegetables. In the absence of sufficient rain, irrigation not only aids the growing crop but permits more thorough and timely soil preparation and planting. It helps insure prompt emergence of seedlings and establishment of good stands. Throughout the season irrigation indirectly aids cultivation. Harvest of root and tuber crops is sometimes very difficult without irrigation to put the soil in a nice, workable condition.

Irrigation takes lots of water. In terms of ordinary household usage, irrigating a large backyard garden or a farm garden may require amounts that appear enormous. The home gardener who proposes to provide irrigation from the household or barnyard well or from the public domestic supply should first estimate if ample water is likely to be available at reasonable cost.

As an example, consider a garden 60 by 70 feet, approximately one-tenth of an acre. Suppose this garden is in a district that normally depends on rainfall but still needs additional water from time to time during the summer and early fall—a good watering during a half dozen short dry spells. Under average conditions the equivalent of an inch of rain may be considered an adequate single application. That amounts to about 2,700 gallons for one application. The cost is not likely to be prohibitive, in view of benefits to be derived, but that much water might not be available at one time.

Quality of water is important for the irrigation of vegetable crops. The content of soluble salts in irrigation water must be relatively low for some crops in order to attain satisfactory yields. The United States Regional Salinity Laboratory lists garden beets,

kale, asparagus, and spinach as having high salt tolerance and radish, celery, and green beans as having low salt tolerance. Other vegetable crops are rated as medium between these two extreme groups. The vine crops are close to the low-tolerance group.

Water applied to vegetables to be consumed in the raw state must be free of micro-organisms associated with human or animal disease, sewage, or spoilage of foods and other organic matter. This requirement might well eliminate from use on some vegetables water from contaminated wells or streams that is still suitable for irrigation of many other crops.

THE AMOUNTS of water required during any season depend on the difference between the use of water by the crop and the effective rainfall received. Five inches of water received in a month may be far less effective when it falls as one 5-inch rain than when it falls in five 1-inch rains, for example. Consequently the intensity of rainfall must be considered as well as the distribution and total amount during the season in determining the amount of irrigation water likely to be required.

Average amounts of water used by vegetable crops vary from 0.10 to 0.20 inches a day, and peak rates as high as 0.32 inches a day have been reported. Consequently the moisture requirement of vegetables might be expected to vary from a low of about 3 inches to a high of 9 inches a month, depending on the crop and the conditions under which it is grown. Potatoes, tomatoes, beans, and sweet corn are reported to have higher water requirements than many other vegetable crops.

It is hardly feasible to give any definite figures for the total amounts of irrigation water needed to grow various vegetables from planting to maturity because those amounts are determined by many factors besides the kind of plant. The amounts of water from snow or rain already in the soil at planting time, the amount of rain that enters the soil during the growth of the crop, the water-storing capacity of the soil, and even the fertility or crop-producing capacity of the soil all influence the amount of water that may need to be added for best results. At the same time it is possible to indicate the relative amounts of water generally required by different garden crops.

The Agricultural Experiment Station of California has estimated the amounts of irrigation water needed for different vegetables in a region of very low rainfall, where most of the water supply must come from irrigation. Those estimates, which assumed that the root zone of the soil was well supplied with water at the time of planting, may be summarized as follows:

Winter lettuce and peas, 6 inches of water; spinach, 9 inches; cabbage, cauliflower, spring plantings of bush beans and lima beans, 12 inches; onions (other than the late crop), pole beans, cucumbers, and watermelons, 15 inches; summer and fall lettuce, sweet corn, bush beans (summer plantings), beets, carrots (except in the Imperial Valley), eggplant, peas (including winter plantings in the Imperial Valley), peppers, squash, muskmelon (except in the Imperial Valley), and sweetpotatoes, 18 inches; potatoes, 20 to 30 inches, depending on season of year; asparagus, 20 inches; late onions, carrots, and muskmelons in the Imperial Valley, and tomatoes (except in cool coastal areas), 24 inches; celery, 30 inches.

The length of time a crop occupies the soil obviously is one of the biggest factors that may determine the total amount of water needed. If a succession of short-season crops with small requirements is grown, the total requirement for the season may be as great as for some long-season crop. In regions receiving appreciable rainfall less than the foregoing amounts will be needed as irrigation.

In the small, backyard garden, where many different vegetables are grown close together, it is generally

impractical to apply different and specific amounts of water to each kind of crop. Good results from irrigation can be obtained by applying a good average amount, based on the soil conditions (the amount of water the root zone will hold), and the weather. Obviously the plants will need less water while they are small and the weather is cool or moist than they will when they are larger or when the weather is hot and dry. There is no substitute for experience in developing good judgment on how much water to apply and when, under any particular set of conditions. There are, however, some general rules that will help guide the gardener in working out his own problem.

SOIL PROPERTIES affect irrigation practice to a great degree. It is important to have some understanding of the relation of kinds of soils and amounts of water they will hold. The kind of soil largely determines how much and how often water needs to be applied. The coarser the particles that make up a soil the less water it will hold under most field conditions. Sandy soils hold only about one-fourth inch equivalent rainfall or irrigation water per foot of depth. Sandy loams commonly hold about three-fourths inch of water per foot; fine sandy loams, about 1.25 inches; silt loams, clay loams, and clays, about 2.5 to 3 inches. These rough figures differ considerably among soils and according to the amounts and conditions of organic matter present in the soils. Large amounts of organic matter may increase the water-holding capacity of the sandy soils and sandy loams and make it easier for water to soak into the heavier soils such as the loams, silt loams, and clays.

One also needs to know what lies below plow- or spade-depth of the soil. The general methods for watering the average garden may have to be modified if subsoil conditions are unusual.

Some surface soils that look all right on the surface are underlain by a hard, tight layer a few inches below plow depth; roots and water can enter it little, if at all. This layer, therefore, results in a shallow zone, in which roots can develop and from which they can absorb water and nutrients. Normal root development may be prevented. The limited amounts of water that can be held by such a shallow layer is soon exhausted in dry weather, and the plants suffer for water relatively soon after a rain or irrigation. Rock near the surface of the soil is even more unfavorable in this respect. Under such conditions water must be supplied in moderate to small amounts frequently. Heavy watering may virtually drown the plants by overfilling the soil pores and preventing proper aeration of the root zone.

In contrast to the existence of rock or hard layers near the surface, some other surface soils are underlain by very open, deep deposits of sand or gravel. Roots can pass readily into such coarse layers but may obtain little water. Crops on soils having such open subsoils containing little water suffer quickly for lack of water just as do those above a tight layer near the surface. They, too, must be irrigated lightly and frequently. Heavy watering of such soil not only wastes water but leaches some plant nutrients down to levels where the roots fail to reach them.

FERTILE SOILS respond best to irrigation. Irrigation is one of the best forms of insurance for success that the gardener can have, but irrigation supplies only water. It will not make up for deficiencies in organic matter, mineral nutrients, weed control, varietal adaptabilities, or other essential features of a good garden. In fact, whether or not irrigation pays in borderline situations may depend more on the factors just named than upon the normal supply of water as snow and rain. Irrigation costs time and money in any situation. There is little point in supplying water to crops that are unable to make productive use of it because of poor soil or poor management.

Some experiments in the southeastern United States show that irrigation as such is far more profitable on soils well supplied with fertilizers and with organic matter from manures and green manures than on soils not so supplied. Plants need plenty of fertility to be able to use water, just as they need plenty of water to use nutrients present. With ample irrigation, rates of fertilizing and manuring can often be increased profitably above the amounts considered to be optimum without irrigation.

THREE METHODS of irrigation are commonly used in home gardens: Furrow, sprinkler, and porous or perforated hose. The conditions in the average farm or backyard garden are generally unfavorable for the use of flooding, although it is sometimes practiced. In locations where subirrigation is feasible, as on certain muck deposits, or on sands overlying a level, watertight subsoil layer, that method may be used. The method most suited to garden irrigation at any particular locality will depend on the factors discussed on pages 341–376, just as it will for other crops. The shallower the depth of rooting of the vegetable crop and the less water the soil can hold, the more frequently the applications must be made and the greater are likely to be the advantages of sprinkler or porous-hose irrigation, as contrasted to the furrow method. The sprinkler or porous-hose method must be used on land having contours not suitable for surface irrigation.

For preplanting applications to aid in germination and emergence of seedlings, furrow irrigation has advantages on soils that are very heavy or that tend to form a crust. The pounding action of heavy drops from a sprinkler may increase the tendency of a soil to form a crust upon drying. If, however, repeated light applications can be made by fine sprinkling to keep the surface moist during the emergence period, this may be the most desirable method. The cost of equipment and of operation must be considered in determining the most satisfactory method of application.

Fixed sprinkler systems are most convenient to use and have long been popular, but they are relatively more expensive than portable sprinklers per unit of area of land irrigated. Fixed sprinkler systems may stay in place for an entire season or even for many years. Straight runs of pipe mounted on top of posts and with suitable nozzles at about 18-inch intervals produce a fine "rain" with a minimum of packing or splashing of the soil or of physical violence to delicate plants. Water for this type of sprinkler must be quite clean, lest particles of debris clog the nozzles. Rotating sprinklers on fixed risers from underground pipes are sometimes used, but they give less even distribution than the pipelines with nozzles at short intervals. Fixed installations with valves and turning devices at the ends of the lines for control of the water reduce need for walking on wet soil or disturbing wet plants, as may be necessary in moving portable sprinklers.

Portable sprinklers are recommended where costs of equipment must be kept down and where moving of the sprinklers is no great problem. They may be of the rotary type, or, for short runs, the nozzle-equipped pipe described above may be moved from one row of posts to another. Quick-coupling unions are available to facilitate moving sprinkler lines of this type.

Several types of rotary sprinklers are available for both fixed and portable supply lines. The choice of a model of sprinkler will depend on the area to be irrigated, the pressure and volume of water available at the sprinklers, and the way the water is to be supplied to the sprinkler. Information on details of sprinkler installations is given in pages 267–273. Ordinary small, portable, fountain-type lawn sprinklers can be used, but they are the least satisfactory of any of the several devices, except for very small gardens. Fountain-type lawn sprinklers cover a small radius and must be moved frequently.

SURFACE APPLICATION by furrow or by perforated or porous hose has its advantages. Many vegetable crops are susceptible to a number of leaf diseases that are aggravated by excess moisture on the leaves. Therefore, a method of irrigation that keeps the leaves dry is often the best. In large gardens and commercial fields the leaves can be kept dry by surface irrigation by furrows, or less often by flooding between borders. Furrow irrigation also has its advantages in the small garden. For both large and small areas the furrow and border methods are practical only when the contours are appropriate and the soil is not so sandy as to result in waste of water.

For efficient furrow irrigation, the soil must hold water well enough to make it possible to wet the soil adequately along the entire furrow without excessive amounts soaking into the soil toward the end where the water is delivered. When the slope is satisfactory, furrow application is better than use of large rotary sprinklers on heavy soils because furrow application causes less packing and crusting of the soil. Furthermore, if water penetration is very slow, water may be applied in furrows precisely where it is needed and run in as slowly as may be necessary to permit it to soak the soil uniformly without waste and without washing of the soil.

In small gardens that are not suitable for conventional furrow irrigation, hose of porous canvas, or perforated hose of various materials, can be used to distribute water relatively evenly along rows of plants.

If water is delivered rapidly from a garden hose or a small pipe into a furrow, the movement of soil can be largely prevented by tieing a piece of bagging or other cloth over the outlet, making a large bag for the water to rush into.

FREQUENCY and rate of irrigation of vegetables require careful judgment just as for other crops. Most vegetables are only shallow or medium in depth of rooting, and the supply of soil moisture available to their roots consequently is limited. Those factors, the high value of the crops, and the importance of time of harvest tend to make management of water for vegetables more exacting than for most other crops.

Most vegetables produce few if any roots deeper than 30 to 36 inches. Many, such as celery, lettuce, onions, radishes, spinach, and peas, produce few deeper than 24 inches. Thus, for the latter group growing in a soil having an available moisture holding capacity of 1 inch per foot to a depth of 2 feet or more, a maximum of 2 inches of moisture should be available to the plant. If the average use rate were 0.2 inch a day, irrigation would be required at least every 9 days unless there is equivalent rainfall. It is well to avoid approaching too close to the complete exhaustion of available water lest error in estimate or unforeseen circumstances cause damage to the crop. During the early part of the season, the depth of rooting would be less and more frequent applications (but of smaller amounts of water) would be required unless the rate of use were correspondingly lower.

Many irrigation farmers are providing themselves with electronic and other devices to indicate moisture content of the soil at different levels and positions in their fields. Such refinements are hardly justified economically for the home gardener. Moderate errors in judgment are not likely to be very costly. The gardener can learn through simple observations and experience when water is needed and about how much to apply. A soil that is very wet will form a tight ball when it is squeezed in the hand and will not crumble when one tries to crush it apart. A soil that is very dry will not stick together when squeezed, but the soil particles will tend to flow through the fingers like dry gravel, sand, or flour, depending on the soil texture. If the soil is cloddy, clods must be broken up thoroughly

before trying this squeeze test. For most vegetables, irrigation should probably be applied when the soil at the rooting depth is just a little bit too dry to hold together after it is squeezed in the hand.

A COMMON ERROR is to indulge in a little superficial sprinkling of the soil surface with a garden hose more or less daily during a dry spell, in the belief that it does some good. Those who do that rarely dig down deeply into the soil to see whether or not it is moist. On heavy soils that have been walked on it takes a long time for an inch of water to soak in. Water running from the soil surface under a sprinkler does not mean the soil is adequately moistened. It only means the water is not getting in as fast as it is being applied. A well-cultivated surface aids penetration of water. Most important, however, is the increase of organic matter in heavy soils to improve penetration of water, and the avoidance of compaction of such soils insofar as feasible.

Crop quality as well as yield can be improved by irrigation. The irrigator should aim to avoid letting the root zone become either very dry or excessively wet at any time. A fairly uniform moderate moisture content is best at all times with the possible exception of the approaching harvest time of vegetable seed crops, when it is well to let the soil become relatively dry.

Wide fluctuations in soil moisture are especially harmful at certain critical stages of plant growth, such as the time of flowering and fruit setting and maturing of fleshy fruits, such as tomatoes and melons. Extreme fluctuation can increase blossom drop in almost any fruiting vegetable crop and is conducive to blossom end rot of tomato. A sharp increase in soil moisture during ripening of tomatoes often increases fruit cracking severely. Too much moisture during ripening of muskmelons tends to prevent development of the highest quality and may cause some fruit cracking. High moisture following very low moisture also tends to increase undesirable "second growth" in potatoes and cracking in sweetpotatoes and root crops. Waterlogging a soil for even a short time can kill many kinds of plants, especially in hot weather. The best yields and crop quality are obtained when extremes of either wet or dry soil are avoided.

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Irrigating Orchards in Dry Regions

F. J. Veihmeyer and A. H. Hendrickson

Our 1.6 million acres in orchards, vineyards, and nut trees comprise about one-fifth of the entire acreage irrigated in 17 Western States and several Eastern States.

Fruit can be grown in some regions without irrigation because enough water from winter rains can be stored in the soil for at least the beginning of the growing season.

Whether and when to irrigate are determined by the moisture properties

of the soil, the kind of plant, its depth of rooting, the kind of root system, climate, and the availability of water.

Methods of irrigating orchards usually depend on the size of stream available, the topography, soil, climate, and the general tendency to follow the practice prevalent in the locality.

For the furrow method, which is usable under many conditions, the slope of the land and the size of the stream used should be such so as not to abet erosion. The furrows are spaced closely enough together so that the wetted areas meet and the water is kept in the furrows until the penetration is uniform. The length of the furrow is regulated so that the difference in penetration between the upper and lower ends is not great.

When only small streams of water are available, furrows or sprinkling, as discussed later, are best. Straight furrows are adapted to relatively flat lands that can be graded to slopes of 0.15 percent or less. Sometimes straight furrows are used on steeper slopes, but then the stream must be controlled carefully lest erosion occur.

Because the size of the stream constantly drops as the water moves down the furrow, more water generally is delivered to the soil near the upper end than at the lower end, and the distribution of moisture may be unequal. The type of soil dictates the length of furrow. On sandy soils the length is about 300 feet; on loams or medium-textured soils, 600 feet is used; on clay soils longer furrows sometimes are used.

Orchards are sometimes irrigated by using very small streams of water flowing through a series of narrow, closely spaced, shallow furrows or corrugations long enough to permit the horizontal seepage from adjacent corrugations to meet. It is known as the corrugation method, and can be used successfully on steep lands.

Another method used on steep slopes is by graded contour furrows, which may be used on lands with slopes up to 25 percent; the grades of the furrows are 0.5 to 1.5 percent, depending on the soil type. Grading is done only to fill gulleys and to remove minor surface irregularities.

The land may be prepared by constructing graded contour terraces and furrows on the terraces. In that way suitable grades for the furrows may be obtained. The grade of the furrows can be reduced by using zigzag or checkback furrows. These furrows permit one to wet the soil between the trees in the row. The furrows are usually graded to slopes of 0.2 percent or less.

Rectangular checks, either for single-tree or multiple-tree basins, are adapted to land that can be leveled to within 0.2 foot per 100 feet. More than one tree can be enclosed in a basin. A long rectangular check is used for a large number of trees. Contour checks, which are used extensively in California, reduce the need for land grading and probably lower labor costs.

Sprinkling can be used under a variety of conditions. Its advantage for irrigating orchards is that it needs no land leveling and small streams of water can be used for it. It is adapted to rolling and steep lands.

Sprinkling requires high capital investment and maintenance costs. Another disadvantage is the limited amount of water that usually can be applied at one setting of the pipelines. The depth of application for a given time, which in orchards is generally limited by 2 moves of the pipelines in 24 hours, is controlled by the rate at which the soil will take water and the discharge rate of the nozzles. Lengthening the time of setting, of course, means increasing the amount of equipment and adding to the cost of the pipe and sprinklers. The inflexibility of operation after the original design of the system is adopted is a disadvantage. Low branches of trees may interfere with the spray from the sprinklers and cause uneven distribution of water.

Water moves downward more because of gravity than capillarity, which may not distribute moisture

uniformly. A light irrigation, however, simply wets a shallower depth to its field capacity than a heavy one does. Soils cannot be wetted partially.

THE LOSSES OF MOISTURE stored in the soil are caused by extraction by the roots of the plants and by evaporation directly from the soil surface. In arid and semiarid regions the major part of the water lost is by transpiration through the plant. In soils in which the water table is not close to the surface, the upward movement of water by capillarity is extremely slow. After the surface layer of about 6 inches has dried, the loss by evaporation almost ceases. Therefore cultivation in order to save moisture by stirring the soil surface is ineffective.

The grower may be able to judge when his trees need water from his daily observation of their condition. When wilting or other evidence of lack of readily available moisture is hard to detect, the condition of some of the broad-leaved weeds, which may be left as indicator plants in various places in the orchard, will show by drooping that they need water. Generally such weeds have deep enough roots to indicate by their wilting a lack of readily available water in the soil occupied by the roots of the trees.

The depth and kind of the root systems of trees and vines are important in determining irrigation practices. Fruit trees, except citrus, and grape vines are in the class of deep-rooted plants. Consequently they can be grown sometimes in regions where there is little rain during the growing season but where evaporating conditions are relatively mild.

It is not true, as some growers believe, that by withholding irrigation, one can make the trees send their roots deeply into the soil. Nor is it true that light irrigation tends to encourage shallow rooting and that irrigating on one side of the tree only will result in confining the roots to that side.

If soils are wet only to a certain depth, and if the soil below that depth is at the permanent wilting percentage, the roots will be confined within the wetted area. But plants that are normally deep rooted cannot be made to keep their roots in the upper layers of soil if those at lower depths have a readily available supply of moisture and if no other adverse condition for root development lies below.

If the soil is wet to the full depth to which the roots would normally penetrate during the growing season, later applications of water during the summer will have no influence on the extent of the distribution of the roots, unless they are frequent enough to produce conditions unfavorable for root growth. The presence of water in amounts above the field capacity, a condition often called waterlogging, may injure the roots of some trees.

Some plants for a part or all of their life span may have sparse root development and the roots do not thoroughly permeate the soil. Consequently large masses of soil may not be occupied by roots. Sampling the soil may not give a true picture of the moisture conditions of the soil that is in actual contact with the absorbing part of the roots. It may then be impossible to determine the amount of available water that can be stored in the soil for such plants or how much water is available at any given time.

COMPACT OR DENSE soils sometimes interfere with root development. Roots will not enter soils that have been compacted by tractor work in the fields. Similar difficulties have been noted on a clay adobe soil. If the roots of the plants do not thoroughly permeate the soil, sampling the soil or depending on an instrument to indicate soil-moisture conditions obviously is futile.

Because soil moisture, from the field capacity down to the permanent wilting percentage, is readily available to plants—for that reason it is called readily available moisture—irrigation is not necessary until the soil-moisture reservoir is drawn down to the permanent wilting percentage. In practice it

may be necessary to irrigate before that danger point is reached. Irrigation must be started early enough so that the last part of the orchard to be irrigated gets water before the trees have suffered.

The growth of fruit is retarded and other symptoms appear when the soil containing most of the roots has been reduced to the permanent wilting percentage. The degree of injury depends on the length of time the soil remains in that condition.

Responses to irrigation may be of two general classes—those in which the response is immediate or takes effect in the season when a change is made in the irrigation treatment; and those in which the response appears slowly and which is sometimes only apparent after several years of following a given irrigation program.

In general, the beneficial results are chiefly those obtained during several years of good irrigation practice. Immediate results are generally harmful ones that usually follow changes in practice involving neglect or failure to irrigate, especially at certain periods.

Increases in yield as a rule are among the benefits that are sometimes slow in appearing and are the reward for the long, continued practice of keeping the trees supplied with readily available water throughout the year.

A smaller size of many fruits, delay in the maturity of pears, and a smaller number of well-filled shells in walnuts are some of the results that immediately follow failure to keep trees supplied with moisture.

The rate at which the fruit grows is a sensitive indicator of whether the trees are getting water. Experiments in California with various kinds of deciduous fruit trees and grapes show that growth of fruit proceeds at a normal rate irrespective of the amount of readily available moisture in the soil which contains the major portion of the root system. When the soil reaches the permanent wilting percentage there is immediate check in growth.

In some sections, where the winter rainfall is ample and the soil holds a comparatively large supply of moisture, some early fruits may be grown to maturity without irrigation and reduction in size of fruit, because the amount of moisture is sufficient to supply the needs of the tree at least until the crop is mature. If there is a scarcity of water it is best to eliminate irrigation in the late season rather than in the early part of the summer.

In general, fruits may be expected to attain normal size if the usual thinning practice is followed and if the soil moisture does not fall to the permanent wilting percentage while the fruits are growing.

The timing of irrigation should not be decided upon because of a certain stage of growth of the plants. The demand for water depends on the size of the plant, sunlight, temperature, humidity, and wind, and not upon the growth stage of the plant.

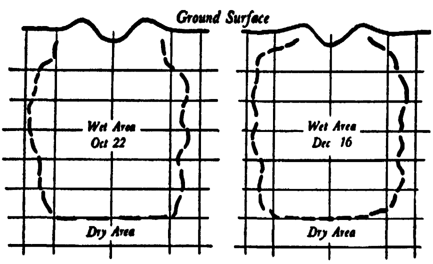
Many growers have believed that irrigation at certain periods of the growing season has an immediate and injurious effect on quality of the fruit.

Our experiments have shown that that is not the case. The highest quality is obtained when the trees are supplied with moisture throughout the year.

Experiments with peaches for canning showed that maintaining readily available moisture in the soil up to and including harvesttime did not injure either the shipping or canning quality. Lack of readily available moisture for several weeks before harvest produced peaches of tough, leathery texture.

Quality in prunes, as measured by the specific gravity, is apparently not greatly affected by the irrigation treatment. It seems to be associated with climatic conditions during the summer. The drying ratios of prunes are not materially affected by the irrigation treatment. They are chiefly dependent on the amount of fruit on the trees. Years of large crops have high drying ratios while those of light crops have low ratios.

Irrigation did not affect the keeping quality, flavor, or drying ratio of table and raisin varieties of grapes. The wines produced from the grapes under different irrigation treatments were remarkably similar if the fruit were allowed to reach maturity.



Water does not move rapidly either upward, sideways, or downward by capillarity, and it will stay until removed by plants. This graph is taken from measurements in an irrigation furrow. The soil is loam. After the water disappeared from the irrigation furrow, a trench was cut across it and the line of demarcation between moist and dry soil was noted. The trench was then covered. Fifty-six days later it was opened, a new face was cut, and the line of demarcation was again determined, but the moisture movement was too slight to measure.

Quality is an intangible characteristic not well adapted to precise measurements, but if analyses such as sugar, acid, firmness, and storage life, can be made, the results have been in favor of the irrigated fruit. Quality cannot be adversely affected by irrigating but may be decisively affected by withholding water.

Experience with orchards and vineyards in California may be illustrative of the water requirements of these crops. The evaporation conditions in the interior valleys of the State are about as severe as those in any other section of the country where fruit is extensively grown. On the other hand, the requirements for other sections of the State with relatively mild climates are also given.

The maximum use of water varies from about 0.1 inch a day in the coastal areas with mild climates to 0.4 inch or higher in the hot parts of the interior.

The following information deals with the seasonal needs under conditions of reasonably efficient irrigation practice and the time and depth of irrigation on the different soil types. It must be kept in mind that the actual use of water by the trees or vines will not be increased by increasing the number of applications because plants cannot be made to transpire more water at high soil-moisture conditions than under lesser amounts of readily available soil moisture. When more than enough irrigations are given than that necessary to insure a continuity of the supply of readily available water, waste due to surface evaporation and deep percolation occurs. If water is cheap, there is a tendency to overirrigate by giving too heavy rather than too light irrigations. Under pumping there is a more conservative practice.

For mature orchards, maximum water extraction from the soil may be as high as 36 acre-inches an acre a season. For the average orchard in the Sacramento Valley, 18 to 24 acre-inches of irrigation water an acre may meet the demands of the trees in years of normal rainfall. On the deep soils of light texture, the water can be applied in three irrigations. If the ground water is at 12 feet or less, deciduous orchards are able to secure a part of their water from that source. Winter irrigation should be gaged by soil-moisture conditions near the end of the winter season. It is poor economy to irrigate soils that are wet to the full depth of rooting.

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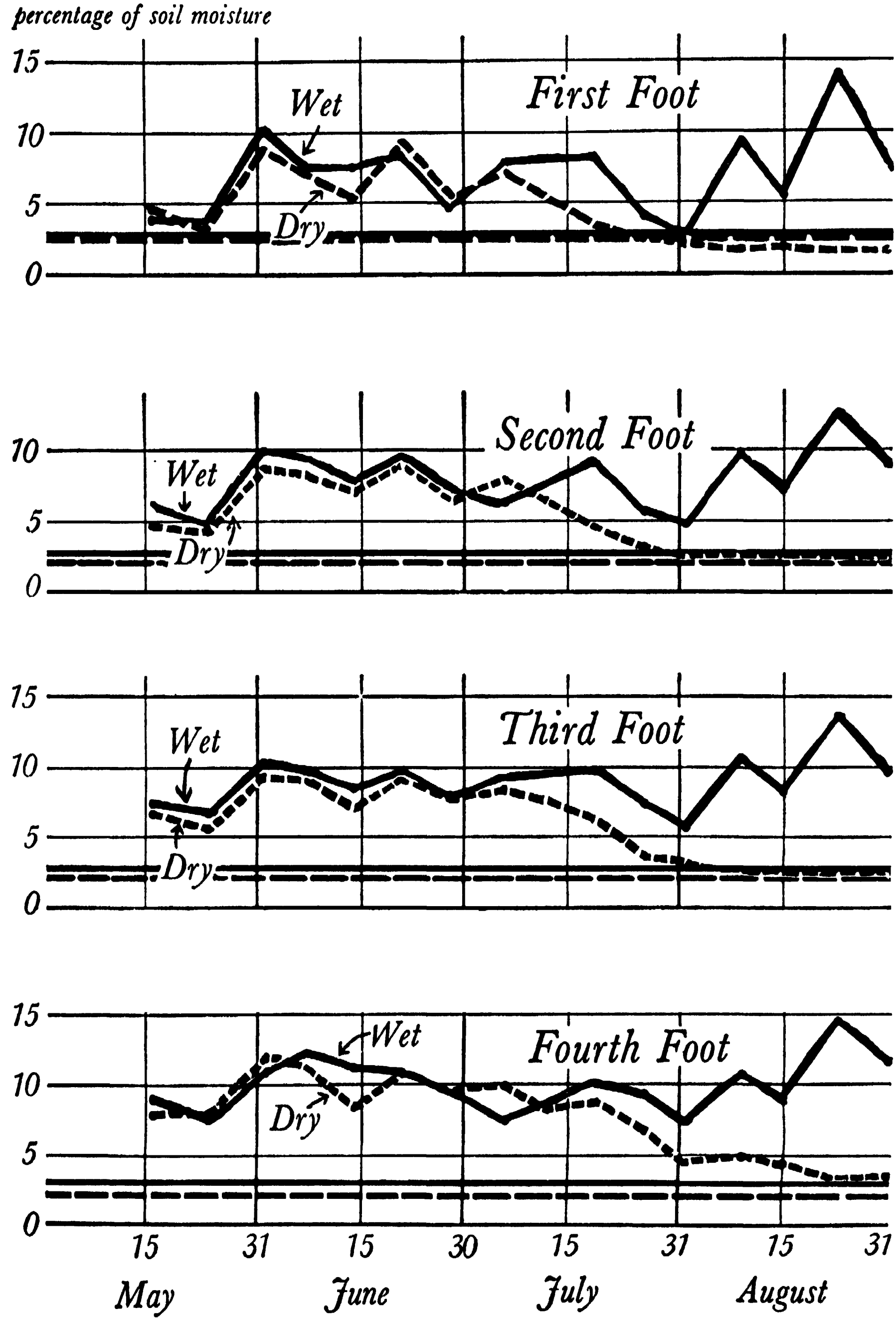
Dr. Veihmeyer and Dr. Hendrickson have been collaborating for many years in studies on plant-soil-water relations. They have been interested chiefly in the irrigation of deciduous orchards and vines.



Soil-moisture contents in a peach orchard. The heavy horizontal lines indicate the permanent wilting percentage of the two treatments.

Watering Lawns and Turf and Otherwise Caring for Them

Robert M. Hagan

Turf grasses probably are injured as often by improper irrigation as by failure to irrigate soon enough. Many people irrigate turf according to habit or custom and pay little attention to whether irrigation is really needed. Yet the proper use of water is one of the most important management practices required to maintain attractive grassed areas.

In the arid and semiarid areas of the Western States, turf grasses must be irrigated throughout much of the year. In the humid and subhumid regions, however, grasses normally need irrigation only during the occasional drought periods to preserve good appearance, and they will generally survive without irrigation.

This chapter is directed primarily to the irrigation problems of dry regions, but the principles and practices I discuss apply equally to the localities where irrigation is needed at times to supplement rainfall.

For established turf the rules of good irrigation are simple:

Water infrequently. Irrigate only when the grass needs water.

Water deeply. Avoid the common mistake of sprinkling lightly every day "just to cool things off."

Why is proper lawn irrigation important? With careful watering one often can: Save considerable water. Reduce watering time and labor costs. Avoid unfavorable soil conditions. Conserve fertilizer. Lessen disease, insect, and weed problems. Permit greater use of turf for recreation. Improve the quality and appearance of turf. If one can achieve any of these objectives by practicing good irrigation, his effort will be abundantly repaid.

The important irrigation problems are: How much water to apply? How often to irrigate? How to apply the water?

No definite answers of general application can be given to the questions. You cannot rely on definite amounts of water and specific irrigation intervals you read about somewhere. Rather, you should realize that your irrigation problem is different—it depends on your soil, your grass, the weather in your vicinity, your irrigation equipment, and other factors I shall mention. Although it will require some analysis and thought, your efficiency as an irrigator easily can be improved if you know what factors govern the amount of water to apply at each irrigation and the proper interval between irrigations. It is also important to understand the operational characteristics of sprinkler equipment.

Before going on, a brief reminder of the water retention properties of soils may be helpful.

Many soils contain about one-half solid material by volume. The rest is pore space occupied by water and air. During irrigation the pores may become almost filled with water to the depth wetted. The soil in this condition is said to be saturated and is a very unfavorable medium for the survival of plant roots. In well-drained soils, one-third to one-half of the water drains away (usually within several days), wetting the soil to a greater depth. The soil then reaches a characteristic moisture content called the field capacity. The amount of water held at field capacity depends on the soil texture, or size of particles present in the soil. Plants growing on the soil will extract water, and if none is added the grass will ultimately wilt. The moisture content at which that occurs is the wilting point. The water held by a soil between field capacity and the wilting point is called the available water. Grass will not suffer for lack of water as long as roots are in contact with available water.

Various soils retain different amounts

of water at field capacity and wilting point; therefore, they have different available water capacities. The available water capacity is easily visualized when expressed in gallons per cubic foot of soil. Typical values per cubic foot of soil are 0.5 gallon for sandy soils, 1 gallon for loams, and 1.5 gallons for clays. It is more convenient, however, for irrigation purposes to consider the inches of available water per foot depth of soil. Using these units, typical values are 0.5 to 0.75 inch per foot for sandy soils, about 1.5 inches per foot for loams, and about 2.5 inches per foot for clays. The figures show why grass on sandy soils requires the most frequent irrigation.

Small amounts of water applied to a dry soil will moisten only a very shallow depth. Below this layer the soil remains dry. If more water is applied to a soil already wet, the surface soil will not retain this additional moisture, and the soil will be wet to a greater depth if the subsoil is permeable.

If the subsoil is impermeable, continued applications of water after the soil has been wet will fill all the pores with water to the exclusion of air, thus creating a waterlogged condition. Air is necessary for the normal functioning of grass roots, and they will be killed by the continued exclusion of air through excess soil water. Lawn grasses will generally survive even though the deep roots have died. Because of shallow rooting, these lawns will require very frequent irrigation despite abundant moisture at depths where grass roots should be active under favorable conditions.

Many sprinkler systems do not apply water uniformly over the entire lawn. Even if they do apply water equally, differences in the ability of the soil to take water often result in failure to wet a uniform depth. The places that receive less water will dry out early. Water may soak in very slowly, because the soil has unfavorable texture, is compacted, or in some localities has become dispersed by sodium salts. Water penetration may be poor over the entire lawn, but more frequently it is distinctly worse in small areas. In such situations water must be applied very slowly over a long period to wet the soil to an adequate depth.

Water may penetrate, slowly, soils of all textures, but clay soils most frequently give trouble. The surface cracks that appear in some clay soils on drying facilitate the infiltration of water. Foot traffic on lawns, particularly when they are moist, will compact any surface soil, especially clays, and lower the rate of water penetration.

The depth of soil permeated by grass roots is important. The deeper the roots, the larger the supply of soil moisture upon which the grass can draw, and the longer the period before irrigation will be needed. Similarly, the deeper the roots, the larger the supply of soil nutrients, and the less dependent the grass will be upon frequent fertilization. Deeply rooted turf resists uprooting damage—important especially where it is used for recreation.

How deep do grass roots grow? It is commonly thought that the roots are confined largely to the top 4 or 6 inches of soil. Often they are found to be only a few inches deep; sometimes roots are less than one-half inch long. Where such shallow rooting occurs, it is usually the direct result of unfavorable soil conditions or poor management practices. Deep rooting is encouraged by providing favorable soil conditions and desirable management practices. Claypans, hardpans, or bedrock within a foot below the surface interfere with maximum root development. Two other common causes of shallow roots are keeping the subsoil too wet by excessive irrigation and allowing it to remain dry by light sprinklings.

Grasses will develop surprisingly deep roots if given an opportunity. The various species apparently have different rooting capabilities. For example, on a deep clay soil at Davis, Calif., 1-year old stands of grasses extracted most of the available soil

moisture from the following depths: Bents 1 foot, red fescues 1 foot, bluegrasses 2.5 feet, tall fescues 3.5 feet, and Bermuda-grasses more than 4 feet. Although most of the roots occur within those depths, some extend further. Some roots were found under Merion bluegrass at a depth of 5 feet and under Bermuda at 6 feet. Even under very young stands only a few months old, roots may extend to a depth of a foot or more. The ability of grasses to root so deeply under favorable conditions is not usually considered in the preparation of sites for planting or in the irrigation of turf areas.

The extent to which management practices, including height of cut, fertilization, irrigation, tillage (spiking), and renovation, may alter depth of rooting is uncertain. Research in California has indicated that the rooting depth decreases as the turf becomes older. The effective rooting depths of Merion and Kentucky bluegrasses in 2-year-old sod were only about half those for 1-year sod. Other grasses have shown the same tendency to become shallower rooted with age. Causes for the death of deep roots are being explored to learn whether management practices can be devised to retain them.

How much water to apply in any irrigation depends on the water-retention characteristics of the soil and on the extent to which the grass roots have extracted the water from the soil.

Since the larger particles of sandy soils retain less water, application of a given quantity of water will wet sands deeper than it will the finer textured soils. The drier the soil at the time of irrigation, the more water is required to wet a given depth. If the soil has been dried until the grass has begun to show wilting, the amount of water that must soak into that soil is approximately equal to the quantity of available water held by the soil within the depth depleted of moisture by the grass roots. The quantities of water required (expressed as depth in inches) which must soak into typical soils to wet them to certain depths are given in a chart. For example to wet a 1-foot depth requires 0.75 inch of water for sands, 1.5 inches for loams, and 2.5 inches for clays. Where surface runoff occurs, the total amount of water applied must exceed the depths indicated in the chart by that lost in runoff.

Most turfed areas are irrigated by portable or permanent sprinkler installations. Efficient irrigation depends upon selecting a correct running time for the sprinklers. They should be run long enough on any soil to restore all the moisture that has been extracted. Wet the soil to the full depth that the grass roots can be expected to grow.

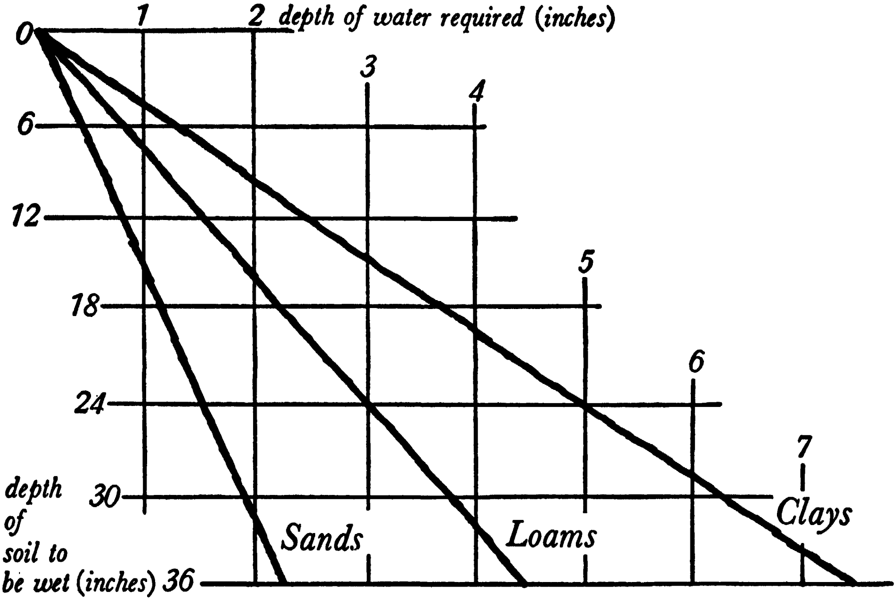
One can determine the correct running time for the sprinkler system on his soil by the following procedure: Allow the grass to remove the soil moisture and reach the condition of dryness which you will habitually select for beginning irrigation; turn on the sprinklers to give good overlapping coverage; record the time required to restore the moisture in the root zone by using a sampling tool, shovel, or sharp-pointed probe.

The correct running time for your sprinklers can be approximated in another way: Estimate the depth of water required to wet the soil through the depth which is noticeably dry (see the chart); measure the depth of water applied at random locations over the lawn area by using empty coffee cans as rain gauges; determine how long it takes to collect the average depth of water required.

If sprinklers are operated through a water meter, the average application rate can be easily computed in gallons per minute by taking the difference in meter readings over a 10-minute period. Then the time needed to apply the depth of water required (as estimated from the chart) can be calculated using the following formula:

$$\text{Time (hours)} = \frac{D \times A}{96 \times R}$$

In the formula, D is the depth of water required (in inches); A is the



Surface inches of water required to wet dry soils to given depths assuming no surface runoff. How to read the chart: Assume a 12-inch depth of loam soil is to be wet. Run down left-hand scale to 12-inch line, then across chart to intersection with diagonal line labeled "loams," and then project line vertically up to scale across top of chart. Depth of water required is 1.5 inches.

area covered (in square feet); R is the application rate (in gallons per minute).

You will be surprised how long it takes to apply the right depths of water. For example, to wet a 1-foot depth of loam soil that has been dried approximately to the wilting point requires about 1.5 hours if the application rate is 1 inch per hour (approximate rate for fixed head spray-type sprinklers) or 6 hours if the rate is 0.3 inch per hour (approximate rate for rotary sprinklers). To wet equal depths of sandy soils would require approximately one-half as much time. Clay soils would require nearly twice as long.

Once you learn how long the sprinklers must be run to obtain the desired depth of wetting, use this information to control future applications. This will be a fairly accurate guide if the soil is always dried out to about the same moisture content before each irrigation and if the factors controlling the application rate, such as water pressure, remain about constant.

Remember two cautions:

First, do not leave sprinklers unattended for long periods. If more water is applied than the soil will retain within the root zone, the surplus water drains down and is wasted, carrying plant nutrients away at the same time. Often a soggy subsoil is created, which may kill the deeper roots of the grass and of nearby trees or shrubs.

Second, do not turn the sprinklers on for just a few minutes. Most of this water will be wasted by evaporation from the soil surface. Wetting soil to shallow depths develops shallow grass roots, encourages the germination of weed seeds, and in time causes a weak, weed-infested lawn. One should aim to replenish all of the moisture that has been extracted from the soil. However, in some cases this may not be easy because of unequal application of water by sprinklers and slow penetration of water into soil.

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How OFTEN should turf be irrigated? No single answer can be given. The irrigation interval depends on the total supply of available soil moisture within the root zone of the grass divided by the rate of use by the grass and surface evaporation.

Consider the soil as a storage reservoir. The total amount of available soil moisture is determined by the available moisture capacity of the soil per foot of depth and by the effective rooting depth of the grass. Thus the total supply depends on soil texture (sand, loam, or clay) and the depth of soil containing roots that has been wet by rain or the previous irrigation.

How long the supply of available moisture will last depends on the rate of removal from the soil by roots and surface evaporation. The rate of removal, or water-use rate, is controlled by weather conditions, exposure of the grassed area, and competition with other plants. Weather conditions, particularly intensity of light, temperature, humidity, and wind, have a great effect on water-use rates. High rates of use can be expected on bright, hot, dry, and windy days. On the other hand, little water is used on cloudy, cool, damp, and still days. Lawns in the sun must be watered more often than lawns shaded by buildings. Grass shaded by trees, however, will have to be given extra water to supply the water used by the trees. Thus the rate of water use varies from day to day, according to weather conditions, and from place to place.

THE RATES of water use have been determined in some localities for typical summer months. The following approximate rates illustrate the range of values to be expected. In coastal areas blanketed by summer fogs, the use rate may be near 1 inch per week; in dry inland coastal areas partially cooled by sea breezes or hot and humid inland regions, 1.5 inches per week; in hot and dry inland regions, 2 inches per week; and in desert areas, 2.5 inches per week.

Now consider again the question, "How often to irrigate?"

The number of days a grassed area may be expected to go without showing need for water can be estimated by making a simple calculation:

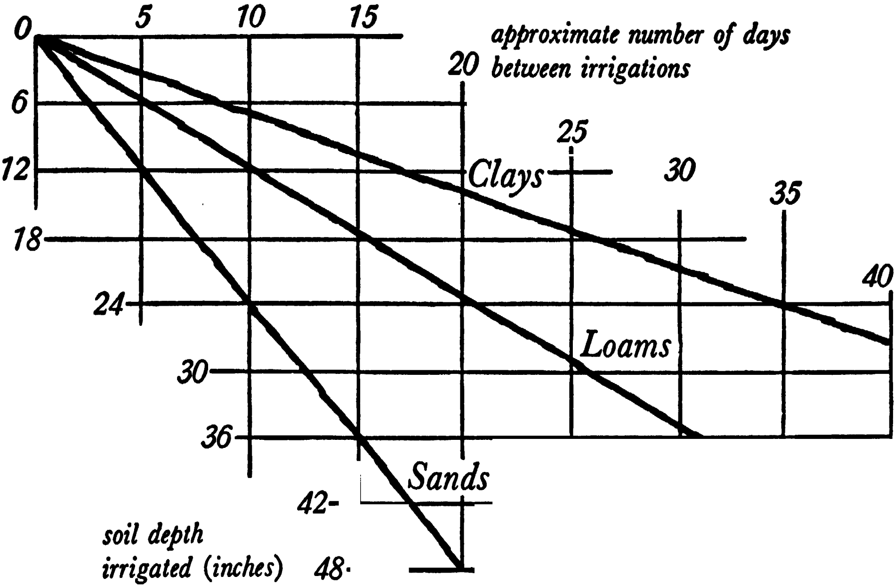
$$\text{Irrigation interval (in days)} = \frac{\text{SAM}}{\text{RWU}}$$

In the formula, SAM stands for the supply of available moisture within the root zone (in inches), which is divided by RWU, the rate of water use (in inches per day).

Consider a grass growing on a loam soil with effective roots to a depth of 1 foot in an area where the water use rate is 0.2 inch per day. If the soil has been wet by previous rain or irrigation through the 1-foot depth, then the soil would contain 1.5 inches of available water within the root zone, according to the chart. Then the approximate irrigation interval equals 1.5 divided by 0.2 or about 7 days.

Approximate irrigation intervals may also be estimated by using the second chart. Where the water-use rate is 1 inch per week, as is assumed in the chart, a grass that has effective roots to a depth of 12 inches should not need irrigation on a sandy soil for nearly 5 days, on a loam for about 10 days, and on a clay for about 17 days. If the grass has an effective rooting depth of 24 inches, then under these conditions the irrigation intervals should be approximately twice as long.

In the humid region, where most of the turf grass area is not irrigated, grasses commonly show no moisture stress even in the absence of rains for several weeks. During prolonged droughts, the grass may dry but is seldom killed. In irrigated regions, however, it is commonly believed that grasses must be irrigated every day or two. The possibilities of infrequent irrigation are being studied by the University of California at Davis, where humidity is very low in summer, and temperatures approach 100° F. on many days. On a deep clay soil, 15-month-old grass plots did not show



Irrigation interval as influenced by soil texture and depth of root zone wet where water use is 1 inch a week. How to read the chart: Assume grass has effective roots to 24-inch depth and soil is wet to this depth. Run down left-hand scale to 24-inch line, then across chart to intersection with diagonal line labeled "loams," and then project line vertically up to scale across top of chart, where you read off about 21 days.

distinct wilting until the following periods had elapsed: Creeping fescues and bents, 14 days; Kentucky bluegrass, 24 days; Merion bluegrass, 30 days; K–31 fescue, 35 days; Zoysia, 45 days; and bermuda, 75 days. After these periods, the grasses, except bermuda, were distinctly wilted but had not turned brown. The bermuda showed no wilting but was growing very slowly.

Perhaps you think, "I can't do this with my turf." You cannot if the roots of your grass are shallow because of shallow soil, age of sod, or management practices that have restricted the development of roots. The experiments at Davis illustrate the importance of deep roots in determining the frequency of irrigation. The creeping fescues, bents, and bluegrasses when 2 years old required irrigation about twice as often as during the previous year. Loss of deep roots with increasing age had reduced their drought tolerance. Grasses that have some deep roots can be allowed to show wilting and considerable browning with little risk of losing the stand. If all roots are confined to a shallow depth, some grasses may die soon after wilting appears. Although allowed to become nearly brown, all grasses in the experiments at Davis resumed growth quickly after irrigation.

Why not consider the results reported here as a challenge to see what you can do to reduce irrigation frequency? Compare your conditions with the above illustrations. Try increasing the number of days between irrigations. When the time between irrigations is too long, you will notice some drying—usually first in small spots. No damage will be done to established lawns if water is soon applied.

If you find that your lawn requires irrigation much more often than you would expect from the examples, check to be sure that you are wetting the soil to the full depth of the grass roots. To do that, you must follow an irrigation schedule that will permit sprinklers to remain in one place long enough to

supply an adequate, but not excessive, depth of water. This may require use of sprinkler equipment that will apply water very slowly. In some instances, surface cultivation of turf areas may help to increase the rate of water penetration. Where soils will absorb only a little water during one irrigation without appreciable runoff, then obviously more frequent irrigations are needed.

Regardless of the season, lawns should be irrigated when the grass shows need of moisture. That means that in winter irrigation may be required occasionally. In summer, irrigation will be needed less often during cool and cloudy weather than during hot spells.

A decided change in irrigation schedules should not be attempted in one jump—especially important if the grass roots are shallow because of light sprinklings or unfavorable subsoil conditions. If light sprinkling has been practiced, wet to a depth of at least 1 foot, if soil conditions permit, and allow the grass roots to extend deeper. If the subsoil is soggy, cut the running time on the sprinklers to prevent adding more water to the subsoil. Then gradually increase the irrigation interval. When the subsoil begins to dry out, increase the sprinkling time to replenish the subsoil moisture. Be careful to avoid excessive applications, which may again create poor drainage conditions. When deeper rooting has been obtained, you should find it possible to maintain an excellent lawn with less frequent watering.

Conservation of water in turf irrigation has become essential in some regions. It is not uncommon to find the use of water for lawns and ornamentals controlled by some type of rationing.

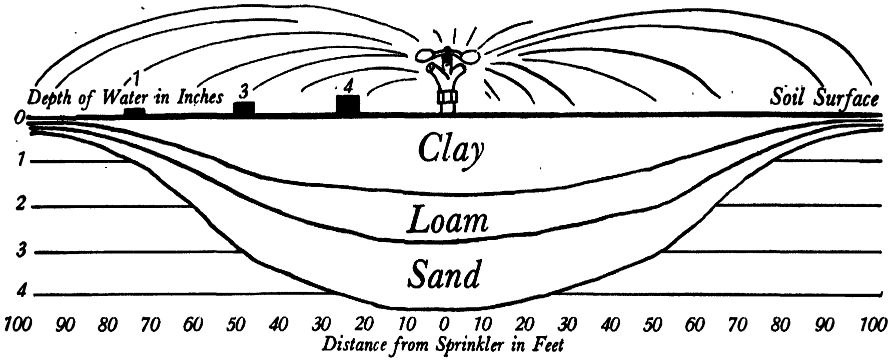
When the water supply is limited, what are the best ways to stretch it?

First, reduce the wastes of water which generally accompany irrigation in the following ways: Avoid surface runoff that often flows into gutters and storm drains. Repair leaky valves and irrigation equipment. Refrain from overirrigation, which wastes water by drainage below the root zone of the grass. Avoid frequent, shallow irrigation—a practice that allows a relatively large fraction of the water supplied to be lost by evaporation. Whenever possible, irrigate while the air is still and water pressures are adequate in order to obtain good distribution of water. Another suggestion: Irrigate at night or in the very early morning, when the humidity is high and air temperature may be low. Very likely evaporation losses from the sprinkler spray and wet foliage can be reduced by doing so; it is probable that appreciable losses occur when evaporating conditions are severe.

Second, irrigate only when the grass actually needs water. As I indicated, every irrigation is accompanied by some waste. In most cases, the fewer the irrigations the fewer the losses.

Third, if water supplies are inadequate, allow the turf to suffer a water deficit for some time before irrigating. It was pointed out that most deep-rooted grasses can be allowed to wilt and even to turn almost brown without much danger of losing the stand. As the surface soil becomes dry and the grasses develop an internal water deficit, the rate of water loss from the soil surface and the vegetation declines appreciably.

The possibility of water conservation by allowing some dryness to develop in turf grasses was studied in a series of experiments at Davis during the hot, rainless summer months. In one of the experiments, the combined water loss from the soil surface and use by Merion bluegrass averaged approximately .19 inch per day during the second week after irrigation while the turf was still well supplied with water. It averaged .17 inch per day in the third week. The average use declined to .09 inch per day during the fourth week as wilting began, and remained at approximately .07 inch per day during the fifth week, as the grass turned brown. Meyer zoyzia on the deep clay soil at Davis showed wilting after about



Distribution of water under a single rotary sprinkler. Depths of water collected in cans placed along surface show progressively less water is applied with increasing distance from sprinkler head. This is reflected in depth of soil wet. To obtain uniform application, sprinklers must be lapped. The depth of soil wet by a given application of water is determined by its texture (sand, loam, or clay).

45 days and slowly turned brown during the next 50 days. It was then irrigated and rapidly turned green. The average daily water-use rate calculated over the 95-day period was less than half that for the first 45 days when the grass was growing. Infrequent irrigation thus offers a way actually to reduce the quantity of water required to preserve a turf area. While some grasses will not survive prolonged periods of water deficiency, most will if grown under conditions where they have developed relatively deep roots.

A common recommendation is to give grass light irrigations by running the sprinklers for only short periods when the water supply is restricted. Actually, however, the most efficient use of water can be made by irrigating infrequently and wetting the soil to the full depth of rooting, if that can be done without appreciable runoff.

Seldom is the quantity of water being used to irrigate turf compared against the water-use rate for the area. A simple calculation will provide a very useful means of checking on the efficiency of your turf irrigation. This can be done as follows:

The water applied over a period can be obtained from your meter readings, water bill, or pump record. Dividing the total gallons applied by the time period in days, gives the average application rate in gallons per day. The turf area irrigated with the water can be measured and expressed in suitable units. Assuming that the water applied was uniformly distributed over the whole area during this time period, then average depth of water applied expressed in inches of water per day is given by the following relations:

For large areas,

$$\text{Water applied (inches per day)} = \frac{36.7 \times \text{water applied (gallons per day)}}{1{,}000{,}000 \times \text{area irrigated (acres)}}$$

For small areas,

$$\text{Water applied (inches per day)} = \frac{1.6 \times \text{water applied (gallons per day)}}{\text{Area irrigated (square feet)}}$$

This type of calculation is illustrated by the following example. In a locality where evaporation from the soil and vegetation was .20 inch a day (for a particular period), 900,000 gallons of water a day were being used to irrigate a 60-acre turf area. How does the quantity of water used compare with the actual water requirement in the area? Using the first formula, it works out that an average of .55 inch of water was being applied. Thus more than twice as much water was used than was required to meet evaporation losses from the soil and plant cover.

Some loss is inevitable, but with care it should be possible to keep a sprinkler-irrigated turf in good condition by applying not to exceed 25 percent more water than the actual losses by evaporation from the surfaces of the soils and grass. Thus, in the example just cited, an average application of .25 inch a day ought to be adequate. Why not check on the efficiency of your irrigation?

WATER IS APPLIED on most lawns by portable or permanently installed sprinklers. A great variety of equipment is available. An efficient irrigation system is not an accident—it requires careful design and selection of the correct units. A poorly planned system may be more of a nuisance than a convenience. It may also be unnecessarily wasteful of water and responsible for poor appearance of the grass.

A detailed discussion of sprinkler design cannot be given here, but some important points to consider will be mentioned. For more details, readers are referred to publications prepared by sprinkler manufacturers and distributors and by a few State agricultural experiment stations or extension services. A few principles to guide one in the use of sprinklers are discussed in the following paragraphs.

A spray nozzle on the end of a hose held by hand or mounted on a stand represents the simplest irrigation system but the most unsatisfactory in many respects. Many home lawns are irrigated in this way. The principal shortcomings of this method are generally the lack of uniform distribution and failure to apply a sufficient depth of water.

A simple calculation should surprise the quick-watering type of gardener. Water can be delivered from a five-eighths-inch hose under typical city pressure at the rate of about 5 gallons a minute. One can easily check the delivery from his hose by noting the time required to fill a 5-gallon bucket or other measure. At the rate of 5 gallons a minute, it takes 10 minutes to apply enough water to wet 100 square feet of sandy soil to a depth of 1 foot. To wet the same area and depth of a clay soil would require about 30 minutes. To irrigate a lawn 1,000 square feet on a clay soil to a depth of 1 foot would take 300 minutes. Few people have the time or patience to irrigate properly by hand. As a consequence, most hand-irrigated lawns are underirrigated and the soil is wet only a few inches deep. Often less than one-half inch of soil is moistened. It is not surprising that when such shallow irrigations are practiced, turf grasses in arid regions must be irrigated almost daily to prevent wilting and discoloration.

ANOTHER SIMPLE irrigation system is a portable fixed-head, rotating or oscillating sprinkler, attached to a garden hose. For relatively small lawn areas, such sprinklers may perform quite satisfactorily. A wide variety of types is available.

The simplest is the nonmoving fountain type. Such sprinklers apply water at a relatively high rate, and runoff may occur within a few minutes on many soils.

Whirling sprinklers are small or medium in size and revolve rapidly. Most have two nozzles, one or both set at an angle so that the reaction of the jet causes the sprinkler head to rotate. Usually one nozzle will cover the area near the sprinkler and the other the outside part of the circular area. Because the water discharged from the head is spread over a greater area, the mean rate of application to the soil is slower, and runoff is less serious.

Slow-revolving sprinklers cover relatively large areas, sometimes 100 feet in diameter. A slow rate of rotation is necessary to obtain maximum coverage. A slowly rotating sprinkler with small nozzles should be used on soils with low intake rates.

Oscillating sprinklers usually have a row of small nozzles mounted on a short length of pipe, which slowly rotates through an arc. These sprinklers

also apply water quite slowly and tend to wet a rectangular area.

Water applied by any single sprinkler is not uniformly spread over the entire wetted area. The stationary and rotating sprinklers tend to have a conical pattern of distribution; the greatest amount of water falls near the head and tapers off to a mere trace at the edge of the area covered. A single sprinkler must be moved from time to time to provide an even coverage. If the sprinkler is moved or used in permanent installations, a lapping of 30 to 50 percent should be allowed.

The greater the area wet by the spray from the sprinkler, the slower is the average rate of application and the longer must the sprinkler be operated in one location to wet a proper depth of soil. A rotary sprinkler coupled to a hose five-eighths or three-fourths inch in diameter under average city pressures may deliver about 5 gallons a minute, and the spray may cover a radius of 40 feet. In such a case, it will take nearly 8 hours to wet a loam soil to a depth of 6 inches at points about 20 feet from the sprinkler. Moving inward from the 20-foot circle, the soil will be wet to increasingly greater depths, while beyond 20 feet the wetted depth will diminish to the vanishing point at about 40 feet from the head.

For many lawns, one rotating or oscillating sprinkler of good design will suffice. Several lawn valves may be desirable for convenience in attaching the hose. Small portable sprinklers may be useful even where an underground system has been installed to spot-irrigate places that require additional amounts of water, perhaps because of competition from trees or other plants.

The underground type of lawn sprinkler has small sprinkler heads set flush with the surface. One need only open a valve to sprinkle the lawn. This type is suitable for automatically controlled systems. Properly designed and installed, it is very convenient. It is relatively expensive to install. Several types of heads are used. The cheapest are the fixed-spray heads, primarily designed for use on small areas, although they may be used on large lawns if the water pressure is low. Fixed spray heads are trouble-free, but each covers only a small area, and a large number of heads at close spacing must be installed. Costs of pipe and installation are high. When spaced for uniform coverage, the average application rate is nearly 1 inch an hour—much higher than most soils will absorb water. Runoff losses are likely to be excessive.

Pop-up spray heads, which rise above the lawn when the valve is opened, are used in large lawns and in turf areas of parks and cemeteries. Like the fixed heads, they apply water at an undesirably high rate. Rotary pop-up sprinklers are also available. Covering a larger area per head with a slow rate of water application, they can be spaced 30 to more than 75 feet apart, depending on the size of the water line and the pressure.

Quick-coupled rotary sprinklers provide a practical and more economical way to irrigate large areas. Quick-coupling valves are hidden in the turf and operate when a sprinkler head of suitable design is plugged into the valve. These systems can be installed at relatively low cost, and when properly designed are convenient and efficient. A few quick-coupling valves, with an appropriate rotary sprinkler, may provide a satisfactory, low-cost system for moderate-sized home lawns.

Some underground systems employ a mixture of spray heads and rotary sprinklers. The spray heads are often used to trim the lawn and cover small irregular areas not conveniently reached by rotary types. Differences in the rate water is applied by these two types of sprinklers must be considered in selecting the proper operation time for each type. To apply a given depth of water over the area, the rotary sprinklers in the system must be run about three times as long as the spray heads.

Before investing in sprinkler equipment, one should study its operating

characteristics, including discharge capacity, area covered, and distribution of water over the wetted area. An important specification is the pressure required at the sprinkler. To obtain the distribution pattern for which the sprinkler was designed, a certain minimum pressure is required at the sprinkler head. When the pressure is too low, the drops are large; more water is thrown to the outside edges of the area covered. A typical example of inadequate pressure is the doughnut pattern—an area near the head receives little water and soon dries out. When the pressure exceeds the design pressure, the spray is broken up into very fine drops, or "fog," so that much of the water is deposited near the sprinkler head in still air or is carried away if it is windy. Variations in pressure affect the patterns of some sprinklers more than others. Pressure also affects the discharge capacity of the sprinkler. If the pressure is doubled, the discharge is increased by a factor equal to the square root of 2. Thus the discharge is increased by 41 percent.

California Agricultural Extension Service Circular 134, *Lawn-Sprinkler Systems*, by J. E. Christiansen, gives the following details.

Eight steps in planning and installing an underground sprinkler system are: Determine the available static water pressure; make a sketch of turf area; select and locate the control valves; select and space the sprinkler heads; determine the number of sprinkler heads on one line; select the size of pipe on the basis of friction loss in pipes and resistance of water meters, valves, and fittings; install the system, allowing for settling of the soil; and adjust the sprinkler heads as needed.

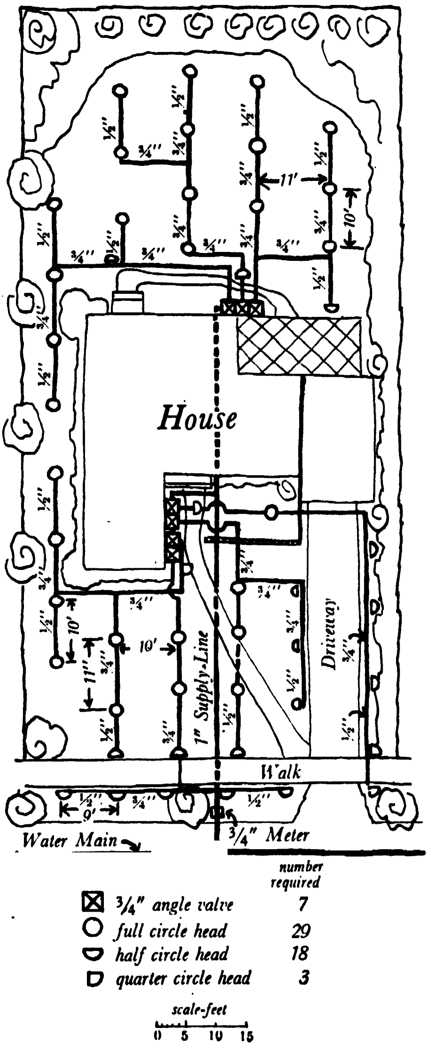
Available static pressure should be measured by attaching a pressure gage to any faucet. The test should be made at an hour when most of the sprinkling is done in the neighborhood to obtain the minimum pressure.

A sketch of the yard showing location of house, walks, drives, lawn areas, gardens, water-supply lines, and available connections should be made on a scale of not less than one-fourth inch per foot. The system then can be completely mapped out on paper and the correct sprinklers, fittings, and pipe selected. The plan for a 60-foot lot in the accompanying sketch illustrates the points to be considered. If you cannot design the system, the sketch, on which are indicated the dimensions and the available pressure, can be used by dealers to prepare a plan for you.

Control valves should be selected and located with particular care. The ideal valve is of rugged construction, offers little resistance to flow, and does not leak when it is closed. Angle valves are most satisfactory for sprinkler installations, and they should be provided with a union connection. Locations next to walks or porches, and far enough away from the nearest sprinkler heads to avoid the spray, are most desirable.

The sprinkler heads must be placed close enough to cover the entire area as uniformly as possible. Sprinklers may be arranged in a square or triangular pattern. The latter arrangement allows a greater spacing between heads with a given sprinkler type. Sprinklers having a cone-shaped pattern (where the amount of water applied decreases steadily from the head outward) are most suitable for overlapping to give a nearly uniform application over the irrigated area. With such sprinklers, it is best to place them at distances equal to the radius of the area wet by each head. That means that the spray from one just reaches the head of another. Half-circle heads are available for installation along walks and borders and when properly spaced may be used to wet corners so that quarter-circle heads need not be installed.

The maximum number of heads to be installed on a line under one control valve depends on: Available pressure at the main, total resistance or pressure loss in the supply line between main and sprinklers, the capacity of sprinkler heads (see the manufacturer's data table) and the arrangement of sprinklers—whether on a single, continuous



Sample design for an underground sprinkler system on a 60-foot lot.

line or in two or more branch lines. When too many heads are installed on one line, the pressure at the sprinklers will not be adequate for proper distribution, coverage will be reduced, and dry spots will appear between heads. Although no harm results from installing fewer heads on one line than is feasible, greater economy is obtained by arranging the layout so as to require a minimum number of valves.

In sparsely settled areas in which new homes are being built, however, it may be wise to plan the system on the basis of a considerably lower pressure in the main than may now be available.

Friction loss in pipelines must be considered. The smaller the pipe and the higher the water velocity through it, the greater the friction loss and the greater the pressure drop. For a given flow of water, each foot of one-half-inch pipe will have as much resistance as 12.5 feet of 1-inch pipe. Friction loss tables are available for different pipe sizes. Resistance offered by a pipe depends not only on size but also on roughness of the inner surface. When a pipe corrodes on the inside, frictional resistance is increased. Copper tubing has a smooth inside surface, which corrodes slowly and will maintain a high water-carrying capacity. Noncorroding, smooth plastic and rubber pipes also are available. Water meters, valves, and fittings also cause a loss in pressure. The losses for them vary considerably with different manufacturers. Friction losses are most conveniently expressed in terms of an equivalent length of 1-inch pipe. For example, a 1-inch angle valve has a resistance equivalent to 8 feet of 1-inch pipe; a 1-inch globe valve has a resistance equivalent to 30 feet of 1-inch pipe. One-inch elbows have an equivalent resistance of 2 feet of 1-inch pipe; a side outlet tee is equivalent to 3 feet of 1-inch pipe.

The actual procedure for determining the proper pipe sizes and numbers of sprinkler heads on given lines is rather complicated.

Good workmanship during installation pays dividends in the long run in lower losses of pressure and absence of leaks, which may be hard to locate. On new lawns it is difficult to set sprinkler heads at exactly the right elevation. Often the ground settles and the heads are left too high. To permit later adjustment after the soil has settled, sprinklers are commonly put on long nipples, so that they extend about 4 inches above the soil. After the grass is

well established and the soil settled, the nipples can be easily removed, because they extend above the grass, cut to proper length, and reinstalled. That avoids both sunken heads and high heads, which are hazardous and interfere with mowing. Where there is danger of freezing damage, each sprinkler line should be laid to a waste valve.

Mention should be made of several other types of equipment. To irrigate narrow strips, as between sidewalks and curbs, nozzle lines have been used. Pipe for nozzle lines can usually be purchased locally or drilled and tapped by hand, but it is hard to get the nozzles lined up accurately. Plastic perforated hose has become available. It is cheap and has some advantages over nozzle lines. Canvas soakers are useful for narrow strips or embankments, which are difficult to irrigate in other ways. A number of heads mounted on a length of pipe or connected with short lengths of hose are realtively inexpensive and can be useful for irrigating strips of turf.

For large, rectangular areas or curved strips, selfpropelled traveler sprinklers may be handy. They consist of a rotary sprinkler head mounted on a cart propelled by take-up reel. Models with different capacities and coverage are available, and the speed is often adjustable. However, one caution should be mentioned. At the speeds they are commonly used, they may apply only one-third to one-half inch of water in one pass. If the soil is dry, one-third inch of water will wet only about 5 inches of sandy soil, 2 inches of loam, or 1 inch of clay. For deep irrigations, therefore, more than one pass is required.

But if the rate of application is too high, water may accumulate in puddles or run off soon after irrigation is begun. When this occurs, the normal impulse is to turn off the sprinklers in the belief the soil has been wet to an adequate depth. Actually, only a shallow layer of soil may have been wet. Many sprinklers apply water faster than the soil can absorb it; if this happens, the rate of application should be reduced if possible. Some sprinklers can be provided with smaller nozzles, or the sprinklers may be turned off at intervals to permit the water to soak in before more is applied.

Runoff is often serious when lawns are on sloping land or compacted soils. The accumulation of clippings and matted growth under some types of turf, a condition sometimes called thatching, may also interfere with penetration. Perforators—devices that remove cores of soil to depths of 3 or 4 inches—have been used to improve water penetration.

Sometimes the application of soil amendments is beneficial, depending on the chemistry of the soil. For example, the application of gypsum to soils containing sodium salts may improve soil structure and increase water percolation rates. However, unless such salts are present, gypsum will have little beneficial effect. Lime, which is generally recommended in the East, cannot be used as a substitute for gypsum to improve high-sodium soils, and it will be of little or no help nutritionally on most western soils, which are generally neutral or alkaline. The recently developed synthetic soil conditioners may improve the structure of some soils if properly incorporated during the preparations for lawn planting, but their long-time value will not be known until much further research is completed. Available evidence indicates that the synthetic conditioners have little effect on existing lawns.

Other soil amendments, such as organic matter, sand, or porous minerals must be added in large quantities and thoroughly mixed with the soil to be beneficial. Before planting a new lawn, it may be possible to improve future water penetration rates to some extent by the addition of very large amounts of those materials. At least three cubic yards of peatmoss or manure to 1,000 square feet, or approximately 50 percent by volume of sand or porous amendments, must be incorporated to

give distinct improvement. Unless one is prepared to carry out a major change in soil conditions, better results may often be achieved by leaving the original soil alone.

Even a well designed and installed system may not work well unless some care is given it during operation. For proper performance, grass must be kept from interfering with the spray from heads set flush with the surface. As the turf becomes older, the sod may thicken and leave the heads too low. When this occurs, the sprinklers should be removed and longer nipples installed. Sprinkler heads may become clogged with foreign matter and fail to distribute water evenly. It may be necessary to remove the heads and clean them. If the water pressure falls too low for proper operation of the sprinklers when they are all turned on at once, fewer heads should be used at one time. Low water pressure will reduce the diameter covered by a sprinkler head and cause an uneven distribution pattern. Wind may so distort the distribution as to leave dry spots between heads and along the windward edge. One should do no sprinkling when it is windy.

AT WHAT TIME OF DAY should turf be irrigated? In many places, it makes little difference. One should realize, however, that the time selected for watering may influence both irrigation efficiency and condition of the grass. Highest irrigation efficiencies can be attained when temperatures are low, humidity high, and winds absent. The most uniform distribution of water can be expected when water pressures are ample and there is no wind. As for the grass, it makes little difference when turf is irrigated except in summer, when fungus diseases may be serious. Watering lawns in full sunlight during the heat of the day very seldom harms grass. Occasionally some injury appears in turf grown on tight, slowly draining soils if they are permitted to become nearly saturated during very hot weather. Then the grass and its roots may be damaged—a condition called scalding. Watering early in the day permits the grass to dry rapidly and may reduce the disease problem. An ideal time to water is near sunrise. Watering is less desirable during the afternoon, when temperatures are high, humidities low, and winds may be strong. Water pressures are often low during the late afternoon and early evening. When lawns are irrigated at that time, the grass will remain damp all night—an encouragement to disease if nights are warm.

NEW LAWNS present special irrigation problems. Before seeding, the lawn site should be thoroughly irrigated to facilitate settling and provide the subsoil moisture needed to encourage deep rooting of the grass. It will be difficult to do so after the seed has been planted. If the seed is sown in dry soil, it is not necessary to irrigate immediately if it is not convenient. Once the soil around the seed has been moistened, however, it is necessary to keep the surface soil continuously moist until germination is complete. One or two light sprinklings a day during the germination period should be enough for most soils during warm weather. A fine spray should be used to avoid washing the soil and dislodging the seed.

After the seedlings have emerged, they may be killed by damping off fungi, particularly if the stand is dense. These organisms are most active when the surface soil is damp. Its spread can be retarded by avoiding late afternoon sprinkling and allowing some drying of the surface soil. Suitable fungicides may also be applied. If the surface is allowed to become too dry, however, some of the more slowly germinating (but most desirable) species may be killed and only the more rapidly germinating nurse grasses may be left.

When the grass is up, the interval between sprinklings and the amount of water applied at each sprinkling should be increased gradually. As the grass becomes well established, one should

slowly extend the irrigation interval by delaying irrigations until the lawn begins to show some signs of drying.

Other turf problems are affected by irrigation practice. Among them are soil compaction, fertility, salinity, diseases, insects, and weeds.

Packing of the surface soil by foot traffic or maintenance equipment is a common cause of thin and weedy turf. It prevents deep rooting and causes poor penetration of water. Compaction can develop on all soil types but is most troublesome in clay soils and those composed of a wide range of particle sizes. If the soil has been compacted, water must be applied slowly for a long time to obtain penetration; even then, it may be difficult to get uniform and deep penetration, and relatively frequent irrigation will be necessary. However, the more often a soil subject to compaction is irrigated, the greater the opportunity for more packing of the surface—and that further retards penetration.

Compaction is most serious when the moisture content of the soil is near field capacity. Relatively dry soils can withstand considerable traffic without injury to their structure. Thus, if turf areas are irrigated only when the grass shows a water deficiency, the danger of compaction can be lessened considerably. One should not walk on the grass until the surface is quite dry. Soil perforators, which remove cores of soil without disturbing the turf, can be effective in improving water penetration on compacted soils. They must be used at frequent intervals for best results.

Irrigation practices can modify the supply of soil nutrients available to plants. To absorb nutrients, roots need water and air. Overirrigation on poorly drained soils fills the pore spaces between the soil particles with water, and air is kept out. Waterlogging the soil prevents decomposition of organic matter and the subsequent release of nutrients. Overirrigation on well-drained soils leaches out nutrients, and makes it necessary to apply fertilizer oftener. Symptoms of nitrogen deficiency are common on overwatered turf.

But underirrigation, by wetting only a shallow depth of soil and confining the grass roots to a small soil volume, also aggravates fertility problems. It is believed that grass roots cannot utilize available nutrients in dry soil. Thus the grass is forced to grow only on the nutrients available in the shallow, moist layer. It is like growing a plant in a small flower pot. The smaller the container the oftener you need to add fertilizer to meet the needs of the plant. When irrigation practices and soil conditions permit the roots to penetrate deeply, the volume of soil from which the grass draws water and sustenance is increased.

The presence of salts in the soil or in the water require that turf be irrigated more frequently. Occasionally sufficient water should be applied to carry the salts down into the soil below the root zone. The washing or leaching of salts from saline soils either by rainfall or by irrigation water is the most general method of improving them. That can be accomplished only if there is adequate drainage. Frequently the accumulation of sodium salts will so deflocculate the soil and impair its structure that downward movement of water through the soil is extremely slow. Then the installation of tile drainage and the addition of gypsum become necessary before suitable turf can be established. Bermuda, Meyer Zoysia, and Alta fescue, in the order named, withstand adverse salt and drainage conditions better than other common turf grasses.

Softened water, as often supplied in the domestic systems of cities in hard-water areas, is a very poor water for irrigation. Where it must be used, some leaching should be provided. Unsoftened water ought to be used for irrigation if possible. Chlorine added for water purification and the copper used as an algaecide in swimming pools will not cause injury to turf grasses.

Turf diseases can often be controlled

or eliminated by the wise choice of irrigation and management practices. Brown patch, pink patch, dollar spot, and helminthosporium are most troublesome in succulent grass during periods of high humidity and temperature. Excessively rapid growth and succulence in turf can be controlled in two ways: Water only when there is an indication of water deficiency, then water heavily. Apply quickly soluble nitrogen fertilizers sparingly when the water supply, temperatures, and humidity are likely to favor succulent growth. Succulence during the summer in dry climates can easily be regulated by controlling irrigation.

Much more research is needed to clarify relations between irrigation and the incidence of disease. The following statements are based on the best available information, but uncertainties exist. Experiments have suggested that turf diseases may gain entrance to the plants through the cut ends of the blades and are aided by the accumulation of "dew", which is composed of condensed water from the air and plant juices exuded from the blades and favors the growth and development of disease spores. If irrigation is withheld until the grass shows dryness, less "dew" will form, the growth rate of the grass will be reduced, and less frequent clipping will be necessary. If irrigation of lawns is confined to the morning hours, when the temperature is increasing and the humidity is decreasing, the grass will remain wet for the shortest period. It is believed that disease under these conditions will be less of a problem.

Brown and discolored patches in lawns during the growing season caused by disease or insects are often mistaken for dry spots. Conversely, dry spots may be mistaken for disease or insect damage. It is necessary to distinguish between the causes before proper corrective action can be taken. That can be done easily. In a recently irrigated lawn, the soil under spots caused by disease or insects will be moist and easily penetrated by a sharp tool. The turf may be only loosely anchored to the soil. In areas where discoloration is caused by excessive dryness, the soil will be dry and hard to penetrate with a pointed instrument.

Brown and discolored spots caused by disease or insects can be improved by applying the proper fungicide or insecticide but cannot be corrected by the addition of more water. Dry spots can be corrected by checking the sprinklers for obstructions in the heads, by watering when the water pressure is adequate for the system or using fewer heads at a time, and by hand watering if the irrigation system is inadequate.

Insecticides used on turf are often soluble in water. Irrigation practices that add more water than is used by the turf unnecessarily dilute the materials and carry them beyond the depth where they are effective. Overwatering practices also encourage succulent grass, which is more likely to be attacked by new infestations.

No single maintenance practice is more important for the control of weeds than proper irrigation. If weed seeds are to germinate and survive, they must be moist at all times until their roots are established. When an established turf is watered only when the need for it is apparent, the surface soil becomes so dry between irrigations that germinating weeds are likely to be killed by desiccation or crowded out by the more deeply rooted turf grasses. Crabgrass, Poa annua, oxalis, clover, moss, and algae thrive under frequent, light sprinklings. Few weeds will survive good watering and good fertilization.

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Drainage of Fields

The History of Our Drainage Enterprises

Hugh H. Wooten and Lewis A. Jones

American farmers since the early days of settlement have drained land. In 1763 the Dismal Swamp area of Virginia and North Carolina was surveyed by George Washington and others with a view to land reclamation and inland water transportation. The Dismal Swamp Canal Company was chartered in 1787 by the two States. The canal was opened 7 years later. It is still a means of transportation and helps to prevent floods.

Early drainage works also were constructed in Delaware, Maryland, New Jersey, Massachusetts, South Carolina, and Georgia. Drainage work of concern to the public was carried out under the authority of colonial and State laws. Among the earliest laws are those of Maryland in 1790 and Delaware in 1816. The North Central States likewise became interested in land drainage shortly after settlement. Michigan and Ohio had drainage laws in 1847.

The early work which started in colonial days, consisted primarily of constructing small open ditches to drain wet spots in fields and of cleaning out small natural streams. Little engineering work was involved. In 1835 John Johnson of Seneca County, N. Y., brought over from Scotland patterns from which clay tile was molded by hand and laid on his farm. That was the beginning of modern tile drainage in the United States.

Settlement of the Ohio and Mississippi Valleys was just starting. Much of this land, though very fertile, could not be cultivated until it was drained, and malaria was prevalent in large areas. Here the use of tile spread rapidly; 1,140 tile factories, mainly in Illinois, Indiana, and Ohio, were in operation by 1880. More than 30,000 miles of tile were laid in Indiana by 1882.

Farmers learned that the success of many tile systems depended on large outlet ditches. The construction of such ditches increased rapidly as the North Central States were settled. The Ohio Society of Engineers and Surveyors reported in 1884 that in Ohio 20,000 miles of public ditches had been constructed, benefiting 11 million acres of land and improving the health of the citizens.

Drainage has added an estimated 25 million to 30 million acres to the tillable area in the North Central States and has increased production on about 37 million acres more.

Typical of the additions to our tillable land are large tracts in northwestern Ohio, northern Indiana, north central Illinois, north central Iowa, and southeastern Missouri. What the tracts were once like is described in the report on Long's expedition to the source of the Minnesota River in 1823,

written by W. H. Keating, of the University of Pennsylvania, who accompanied the expedition. The Long Expedition, undertaken by order of J. C. Calhoun, Secretary of War, sought information about the conditions in the country, then undeveloped, west of Pennsylvania.

Professor Keating described the land east of Fort Wayne, Ind., thus: "Near to this house we passed the State line which divides Ohio from Indiana. . . . The distance from this to Fort Wayne is 24 miles, without a settlement; the country is so wet that we scarcely saw an acre of land upon which settlement could be made. We travelled for a couple of miles with our horses wading through water, sometimes to the girth. Having found a small patch of esculent grass (which from its color is known here as bluegrass) we attempted to stop and pasture our horses, but this we found impossible on account of the immense swarms of mosquitoes and horse flies, which tormented both horses and riders in a manner that excluded all possibility of rest."

He also described the land south and west of Chicago:

"From Chicago to a place where we forded the Des Plaines River the country presents a low, flat, and swampy prairie, very thickly covered with high grass, aquatic plants, and among others the wild rice. The latter occurs principally in places which are under water; its blades floating on the surface of the fluid like those of the young domestic plant. The whole of this tract is overflowed during the spring, and canoes pass in every direction across the prairie."

Drainage changed those conditions. Today, the traveler who notes the well-cared-for productive fields, the substantial farm buildings, the good roads, and splendid school buildings, may not think that drainage made possible many of the developments—that without drainage the localities would be much the same as Keating described them in 1823. In both areas there are now more miles of public outlet ditches and drains than there are miles of public highways.

THE SWAMP LAND ACTS of 1849 and 1850 were the first important Federal legislation relating to land drainage. They were the result of more than 20 years of discussion in the Congress of appropriate procedures for initiating reclamation of the wet lands of the public domain. For more than 75 years they were almost the only statement of Federal drainage policy. Under the acts, vast acreages of swamp and overflowed lands were transferred to the States on condition that funds from their sale be used to build the drains and levees necessary to reclaim them.

Under the Swamp Land Acts of 1849, 1850, and 1860, approximately 64 million acres of swamp and overflow land in 15 States were conveyed to the respective States to facilitate reclamation of the land for agricultural use. No important reservations were attached to this transfer, and the States were free to dispose of the land as they saw fit. In that way the Federal Government relinquished control of most of the potential drainage work in the public domain.

It has become common practice to dismiss as failures the drainage and flood-control projects started under the Swamp Land Acts. It is true that for the most part the States did not immediately develop the land as anticipated. But that is not the whole story.

Over the lower Mississippi Valley States, where administration and use of swampland funds was a major political, economic, and social issue for more than 30 years, reclamation carried out under the Swamp Land Acts permanently affected the agricultural economy. Experiences in flood control and drainage engineering, gained in trying to meet the provisions of the grants, formed the basis for the elaborate drainage projects later undertaken by local districts and by the States and the Federal Government for control of floods in the lower Mississippi Valley. Likewise most of the legal and admin-

istrative concepts and machinery set up under the Swamp Lands Acts became a permanent part of flood-control and drainage practices.

According to the wording of the Swamp Land Acts, the reclamation included both flood control and drainage. But State and Federal legislators alike underrated the complexity and cost of flood control and drainage in the lower Mississippi Valley. Receipts from the sale of swamplands were a pittance compared to the amount required to control floods and improve drainage. Historically the Swamp Land Acts are significant chiefly because of the vast transfer of lands made under them—first from the Federal Government to the States, soon thereafter by State governments to the counties and the levee boards, and later to private citizens and corporations.

Disastrous floods occurred frequently from 1850 through 1900. Loss of life and property led to increased expenditures for flood-control work each year. Flood-control improvements in time grew to an impressive size. With their increasing enlargement, waves of optimism found expression in the development of new land. By 1900 or so, it appeared that public reclamation work should include land drainage besides levee building. Soon the landscape of much of the Delta region was altered through drainage activities initiated and financed through creation of local drainage districts under State laws.

Drainage is a land improvement and cultural practice on about 2 million farms. The agricultural census of 1950 reported nearly 103 million acres of land in organized district and county drainage enterprises in 40 States. More than 900 million dollars, or an average of about 9 dollars an acre, has been expended on public drainage improvements on the 103 million acres, which is larger than the combined areas of Ohio, Indiana, and Illinois. More than 155,000 miles of outlet ditches, 56,000 miles of main outlet tile drains, 7,800 miles of levees, and pumping plants of more than 110,000 horsepower have been constructed. The enterprises range from fewer than 100 acres to more than 1 million acres; they average about 7,300 acres.

Of the 103 million acres in drainage enterprises, some 15 million acres are still too wet for cultivation; crop losses are frequent on an additional 10 million acres because of poor drainage.

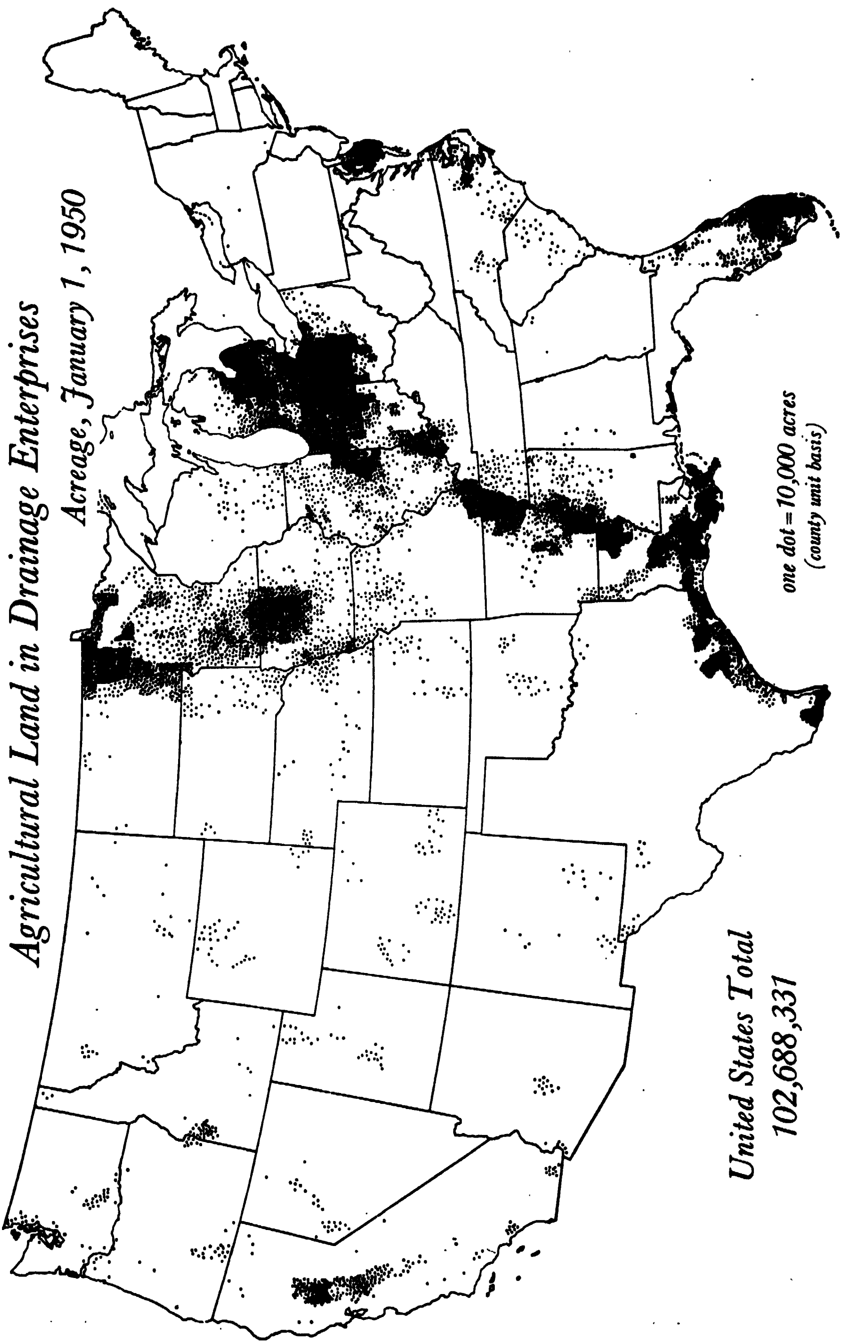
Those unsatisfactory conditions are due primarily to lack of sound engineering in designing the improvements and to poor maintenance.

Besides the land in organized public drainage enterprises, we estimate that more than 50 million acres of wet farmland have been drained by individual, private projects. We have no reliable record as to the amount of money spent or the number of miles of field ditches and tile drains that individual farmers have installed on field drainage, but the expenditure for such work is estimated to be many times the amount spent on outlet drainage.

In constructing public drainage improvements only main outlets as a rule are provided. Before their land can be farmed to the best advantage, farmers usually must install necessary farm drains, clear and level the land where necessary, and otherwise prepare it for cultivation.

The map and tables with this article show where the drained lands are located and the rate at which drainage is done. Land in organized drainage enterprises is largely in the Corn Belt, Lake States, and the Mississippi Delta. Between 1920, when the first census of drainage was taken, and 1950, the greatest increase of land in drainage enterprises occurred in the Delta and Corn Belt States. The Southeastern region had a high proportional increase. The relatively little drainage work done in the Western States has been mostly in connection with irrigation.

Between 1940 and 1950, the land in drainage enterprises increased by nearly 16 million acres. Half of the increase was in the Mississippi Delta. Another


Agricultural Land in Drainage Enterprises
Acreage, January 1, 1950
one dot = 10,000 acres
(county unit basis)
United States Total
102,688,331

Acreage of Land in Organized Drainage Enterprises Regions and by Specified Years, 1920–1950 [1]

Region [2]	1920	1930	1940	1950	Change 1940–1950
	1,000 acres	*1,000 acres*	*1,000 acres*	*1,000 acres*	*1,000 acres*
Northern:					
Northeastern	0	0	578	744	166
Lake States	19, 757	21, 548	20, 730	21, 979	1, 249
Corn Belt	28, 924	32, 700	32, 194	35, 194	3, 000
Northern Plains	2, 164	2, 929	3, 227	3, 457	230
Total	50, 845	57, 177	56, 729	61, 374	4, 645
Southern:					
Appalachian	1, 265	1, 873	1, 908	2, 750	842
Southeastern	1, 843	6, 247	6, 016	6, 506	490
Mississippi Delta	7, 347	11, 275	11, 703	19, 886	8, 183
Southern Plains	2, 178	3, 054	4, 416	6, 096	1, 680
Total	12, 633	22, 449	24, 043	35, 238	11, 195
Western:					
Mountain	810	1, 970	2, 773	2, 671	[3] −102
Pacific	1, 207	2, 812	3, 422	3, 405	[3] −17
Total	2, 017	4, 782	6, 195	6, 076	[3] −119
United States	65, 495	84, 408	86, 967	102, 688	15, 721

[1] Bureau of the Census: Census of Agriculture, 1950, Drainage of Agricultural Lands, vol. 4, 1950.
[2] Including irrigation enterprises that have their own drainage.
[3] Decrease indicated by minus sign.

Drainage Development and Use of Land in Drainage Enterprises in the United States to 1950 [1]

Year	Land in all enterprises	Drained	Improved	In planted crops
	1,000 acres	*1,000 acres*	*1,000 acres*	*1,000 acres*
Before 1870	171	150	133	97
1870–79	428	404	373	288
1880–89	2, 429	2, 267	2, 173	1, 865
1890–99	3, 743	3, 500	3, 256	2, 482
1900–04	5, 769	5, 414	5, 134	3, 814
1905–09	12, 192	11, 081	10, 340	7, 652
1910–14	19, 573	14, 138	12, 281	9, 006
1915–19	18, 012	16, 262	14, 067	10, 268
1920–24	11, 272	10, 028	8, 848	6, 480
1925–29	7, 411	6, 824	6, 188	4, 511
1930–34	2, 093	1, 974	1, 788	1, 326
1935–39	3, 874	2, 962	2, 808	1, 824
1940–49	15, 721	....	14, 749	....
Total to 1950	102, 688	....	82, 138	....

[1] Bureau of the Census: Drainage of Agricultural Lands [1940], 1942; Drainage of Agricultural Lands, vol. 4, 1952.

4 million acres of the increase occurred in the Lake States and Corn Belt.

Texas also had a large increase. The three regions, with Texas and Florida, accounted for three-fourths of the land in drainage enterprises in 1950.

Farm and district drainage sometimes has been aided by the building of major channels and outlets by the Corps of Engineers, particularly in the Mississippi Valley. These new or improved outlets have encouraged the organization or reactivation of many drainage districts in order to improve local drainage ditches and reap the benefits of better main outlet drainage.

Most public drainage projects, however, were undertaken by local drainage districts and counties, and the investment was made chiefly by private citizens through local taxes or special assessments on the property that was benefited. But individual farmers and small groups have had limited financial and technical aid for farm drainage from the agricultural and soil conservation programs when such work contributed to the overall conservation plan for a farm or local area.

Two major forms of organization are provided under the drainage laws.

In one, which may be called the "county form," management of the affairs of the enterprise is in the hands of county officials, who may or may not be personally interested in the enterprise. In the other, which may be called the "district or corporate form," management is in the hands of a board elected by the landowners of the enterprise. Both forms operate effectively when they are well administered. Under both forms, drainage work can be financed by sale of bonds, which are to be refunded over a period of years. The bonds are a first lien on the benefited land in the district; they rank immediately after State and county taxes and ahead of land mortgages.

State laws generally provide the landowner with a means of organizing to obtain drainage improvements, a method of apportioning the cost of the work, the right to levy and collect taxes from all who receive benefits, the right of condemnation against private property for public use, and a method of financing by the sale of bonds to be refunded over a period of years.

Drainage laws in most States have been developed gradually from the time of settlement as larger and more costly improvements have been planned. The many amendments, revisions, and supplemental acts passed by the legislatures sometimes have resulted in inconsistent or even contradictory provisions, so that the meaning must be determined by the courts.

The courts have written decisions on many phases of drainage. They have pretty well established the requirements for such legislation. In attempts to meet the decisions, the States usually have amended and reamended their drainage laws without giving consideration to the law as a whole. In some States the laws make no provision for maintaining drainage works after they have been constructed. In other States methods of assessing benefits are unsatisfactory. In most States the laws establish the procedures and the safeguards necessary in large drainage enterprises that require bond issues, but they fail to provide simple and inexpensive procedures for organizing and operating small enterprises where the work can be paid for in cash. A competent committee organized in each State where drainage is important could profitably study existing drainage legislation and court decisions and prepare recommendations for improvement of existing laws.

Organization of drainage districts requiring bond issues was confined before 1910 primarily to the North Central States. A few districts were in the alluvial area of the lower Mississippi Valley. With the fertile prairie soils and generally smooth lands of the North Central States, engineering problems were simple, cost of drainage was low, and expenses of putting the

land into cultivation were small. Much of this early work proved profitable and made possible development of some of the most fertile and profitable agricultural areas in the country.

Drainage work was continued, with only few exceptions, on a conservative basis until about 1915, when the period of high prices resulting from the First World War led to the speculative development by drainage of large areas of cutover forest, swamp, and marsh in nearly all of the Mississippi Valley and the Southern States. Many of these projects encountered financial difficulties for one reason or another from 1925 to 1940 and required adjustment and refinancing of debt.

In many such districts the promoters failed to take into consideration such items as soil fertility, cost of developing farm units after drainage was completed, cost of maintaining drainage improvements, and markets for the farm products to be grown. Plans for drainage were incomplete in some districts or improvements were designed with insufficient capacity. Large areas remained poorly drained and could not be made to produce profitable crops without extensive additional work. Difficulties in most cases were due to poor planning and piecemeal methods of drainage. Some districts did not employ competent drainage engineers. Many of the projects were unsound from the beginning because the soils were unsuitable for tillage or not sufficiently fertile to warrant development or because lack of control or erosion from surrounding hill lands made it impracticable to maintain the drainage improvements.

To avoid such difficulties in the future, enough investigations should be made by those interested to determine the desirability of drainage enterprises from the soil and land-use viewpoints, to develop sound engineering plans, and to finance the work on a reimbursable basis.

The need for this type of work has been recognized by Louisiana, which in 1940 inaugurated a program of rehabilitating existing drainage enterprises and helping to develop new enterprises. Other States have considered similar programs.

The federal government carried on only a slight amount of direct land drainage before the organization of the emergency public works program in the 1930's. Its functions were mostly advisory or indirect. In more recent years, with the organization of new Federal financing agencies and the corollary expansion of construction work by old agencies, the functions broadened notably.

The nature of these activities generally is defined by legislation only so far as congressional authorization of annual agency appropriations implies approval of the current program. In making appropriations for the work of the Department of Agriculture, Bureau of Reclamation, and Corps of Engineers, the Congress has authorized certain types of research, financial aid, and construction relating to drainage, particularly where conservation, reclamation, and flood control were involved. Federal assistance with respect to drainage activity also has been provided specifically by the Congress in other ways.

The Congress has granted rights-of-way and easements to canal and ditch companies for constructing improvements through the public domain. It has authorized a decennial census of drainage enterprises. It also authorized the Federal Reserve Bank to buy and sell drainage district securities, authorized bankruptcy courts to receive petitions from drainage districts for readjustments of debts, and empowered the former Reconstruction Finance Corporation to finance refunding operations for existing drainage projects. Thus Federal concern from 1925 to 1940 was chiefly with rehabilitation of enterprises suffering economic distress. A considerable part of the distress was due to ill-advised and speculative de-

velopment of drainage projects by non-Federal interests in the past.

In the Flood Control Act of December 22, 1944, the Congress authorized work on channels and major drainage improvements as a part of the national flood-control program. Under the act, main channels and outlet ditches that serve many existing enterprises can be improved if the work is of widespread public benefit. Here the Corps of Engineers were for the first time instructed to engage in drainage work not directly related to levee building and other flood-control projects.

A new stage in Federal policy relating to drainage was reached with the enactment of the Watershed Protection and Flood Prevention Act of August 4, 1954. That act authorized the Department of Agriculture to cooperate with States and local agencies in planning and carrying out works of improvement for soil conservation and other purposes, including land drainage.

IN THE EARLY DEVELOPMENT of drainage work, outlet ditches were constructed by hand or with teams and scrapers. With such methods, the ditch that could be economically constructed could not be more than 5 feet deep; the bottom width seldom exceeded 4 feet. As the size of projects increased, such ditches did not provide the drainage desired.

An economical means of constructing large open ditches was sought. In 1883 the first dipper dredges were developed. For many years such machines were widely used.

The dipper dredge was followed in 1906 by the dragline excavator, which has been in general use since. It is a flexible machine. It is built in many sizes, and can dig ditches 3 to 150 feet in bottom width and 3 to 20 feet deep efficiently and economically. The newest models of draglines generally are diesel-powered and mounted on caterpillar tracks.

Until 1880 or so all tile drains were constructed by hand. As size of tiles and depth of drains increased, a machine that would dig trenches was needed. In 1883 the plumb ditching machine, powered by a steam engine, was placed on the market. Not much later several other steam-operated machines were built. Our modern, efficient tile-trenching machines were developed from them. The smaller machines can dig trenches up to 4.5 feet deep and about 1 foot wide. The larger machines dig trenches up to 6 feet deep and 1.5 feet wide. Operated efficiently under average conditions, a good trenching machine can excavate 2,000 to 3,000 feet of trench a day.

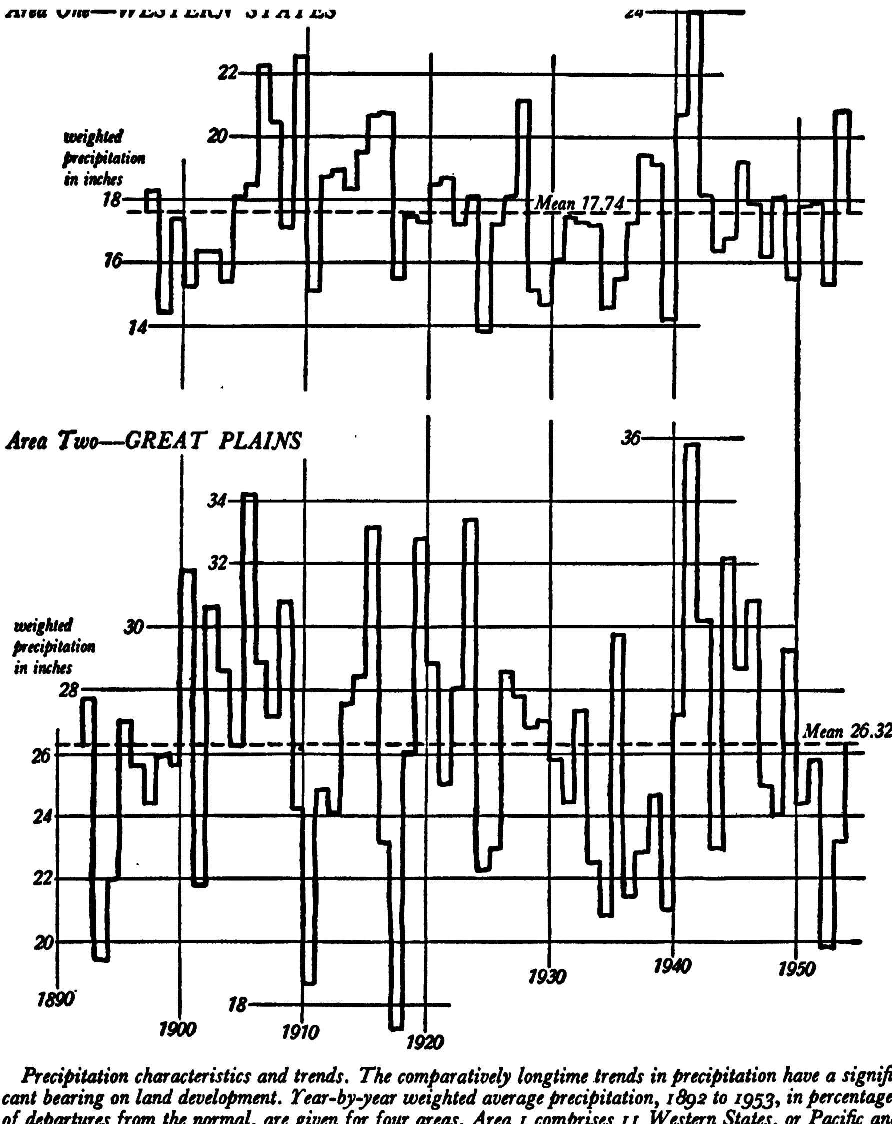
Use of drainage wheels, operated by animal power, to drain lowlands without gravity outlets was early practice among the plantations of the gulf coast, especially on sugar plantations. About 1850 pumps began to be used. As the projects became larger, low-lift centrifugal pumps gradually replaced other types. The wood screw pump was developed in 1915. It is widely used on the larger pumping projects.

The periods of the most land drainage, as measured by the acreage added to drainage enterprises, coincide generally with periods of average and above-normal precipitation. Precipitation was high in the Mississippi Valley and Eastern States from 1900 to 1925, for example, and much agricultural land was drained then. From 1925 to 1940, when precipitation was less, drainage was less active; the increased rainfall of the 1940's again gave drainage a fillip.

An accompanying chart shows the weighted average precipitation in departures from normal for four regions of the United States from 1892 to 1953. An examination of the graphs discloses some interesting trends in comparison with a table that shows drainage development and use of land in drainage enterprises by periods.

Periods of above-average activity in land drainage generally have coincided with or followed periods of heavy demand and rising prices for farm products. For example, drainage construction was heavy from 1909 to 1929,

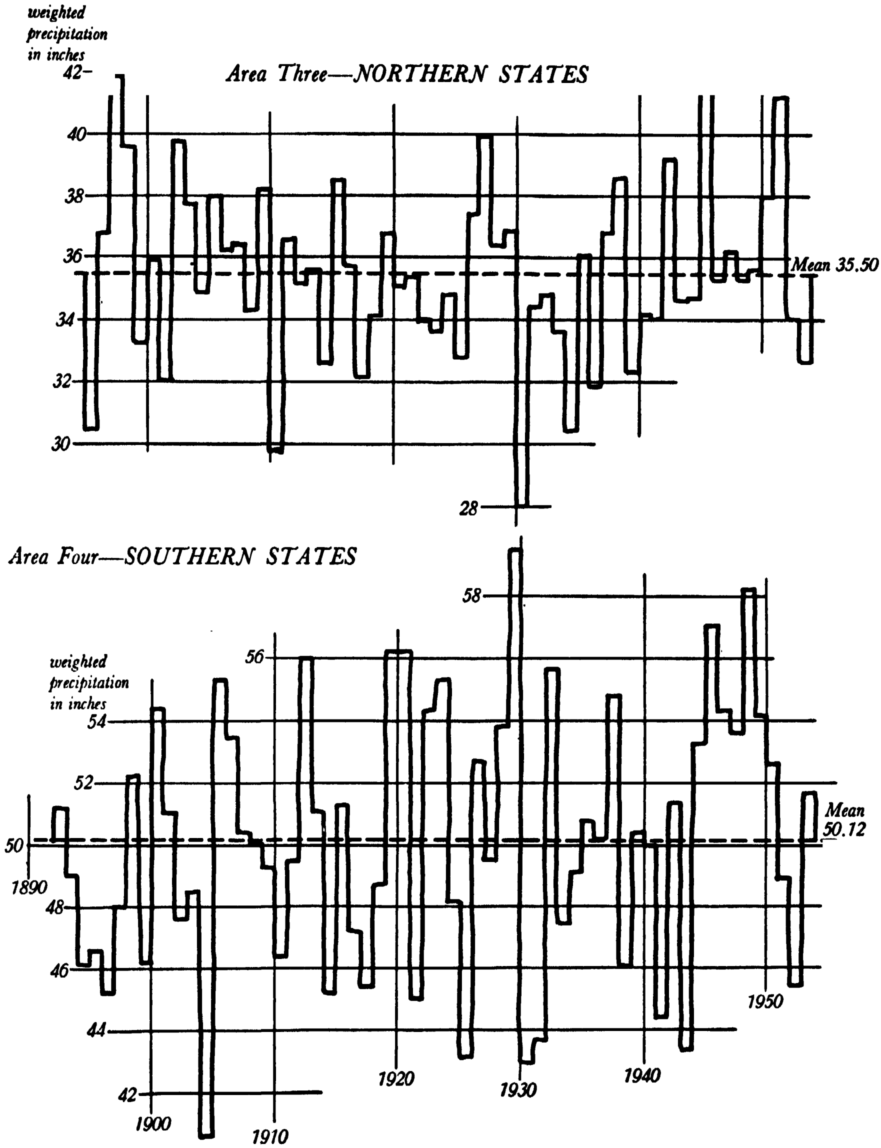
Precipitation Characteristics and Trends



Precipitation characteristics and trends. The comparatively longtime trends in precipitation have a significant bearing on land development. Year-by-year weighted average precipitation, 1892 to 1953, in percentages of departures from the normal, are given for four areas. Area 1 comprises 11 Western States, or Pacific and Mountain States; Area 2, the 6 Great Plains States, North Dakota to Texas; Area 3, the Northern States, including the Corn Belt, Lake, and Northeastern States; and Area 4, the Southern States, including the Mississippi Delta States and the Southeastern and Appalachian States.

when demand for farm production was increasing and when prices and income were considerably above those of the preceding decade. Costs of farming as well as costs of construction, including wages, were also higher during periods of high production and heavy drainage activity. But during periods of low

Precipitation Characteristics and Trends



farm prices, some drainage construction and other types of farmland improvement were made in order to increase crop acreages and maintain farm incomes. Farm production has varied much less than prices between periods of heavy and low demand.

The Engineering News Record Construction Cost Index shows that from 1910 to 1929 construction costs as a whole were less than 40 percent of those from 1949 to 1953. Prices paid by farmers for production materials and labor from 1910 to 1929 were

about 50 percent of what they were from 1949 to 1953.

THE MILLIONS OF ACRES once too wet to be cultivated and since reclaimed now rank among the most valuable agricultural areas of the country. Additional millions of acres, where crop losses were frequently due to inadequate drainage, now produce well.

Twenty-one counties in northwestern Ohio and northeastern Indiana in the area in which there was originally much low land, impossible to cultivate, now comprise one of the most productive areas in the country. According to the 1950 census, this area produced for sale more than 225 million dollars worth of agricultural products in 1949.

The north central part of Iowa has extensive areas of flat land, which comprises about 90 percent of 11 of Iowa's richest agricultural counties. At the time of settlement much of this land was in shallow sloughs, which were wet during so many seasons that they could not be cultivated. The rest of the area could be cultivated, but crop yields were generally low because of lack of drainage outlets. Drainage work was started soon after settlement. Today this extensive area is included in drainage enterprises and has drainage outlets. In 1949 the value of agricultural products raised and sold from the area totaled about 200 million dollars. At least 50 percent of that production would not have been possible without drainage.

In southeastern Missouri one drainage district of 400,000 acres, with other smaller districts, covers much of the agricultural area of five counties. In 1909, before drainage, the only land under cultivation was small patches along streams. Less than 5 percent was cultivated. The rest was swampland. Drainage work was started about 1912. Now 95 percent of the area is under cultivation and includes some of the most valuable land in Missouri. The value of farm products sold from the area in 1949 was more than 75 million dollars.

Large areas in western Minnesota, central Illinois, northeastern Arkansas, the gulf plains of Texas, and the delta areas of Mississippi and Louisiana were originally swamp and overflow areas. Drainage permitted cultivation.

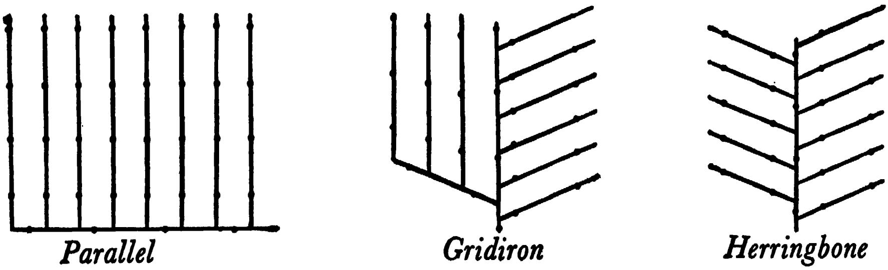
It is estimated that drainage has added 50 million to 60 million acres of fertile swampland to the cultivable area of the United States and that production has been increased on an additional 75 million to 100 million acres.

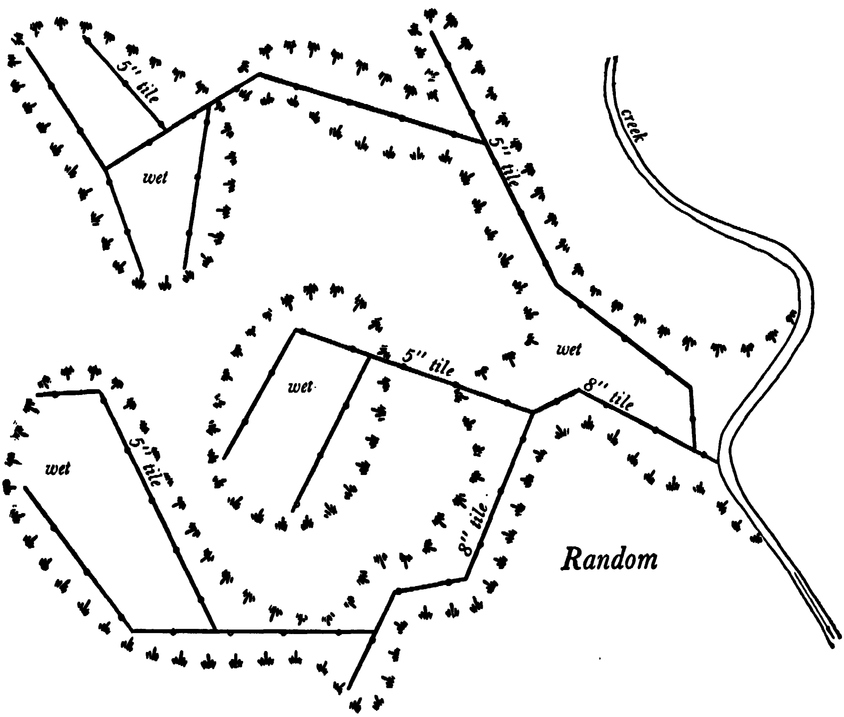
Some mistakes have been made. Some land of little value to agriculture has been drained. It has also been damaged for wildlife. In other areas the plan of drainage proved to be unsatisfactory and too costly. In some places no provisions were made to control sediment or to maintain ditches and other works, and within a few years the drainage improvements were destroyed.

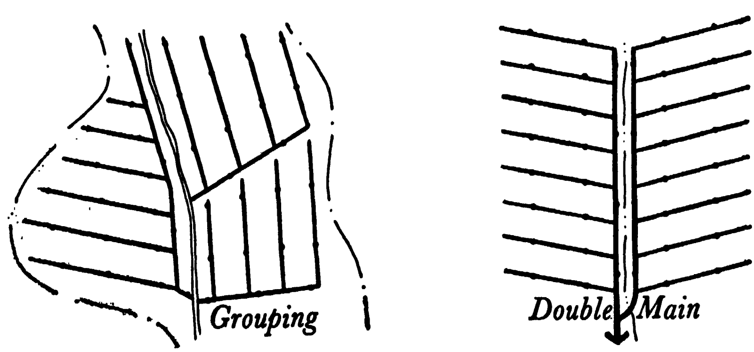
EVERY STATE has some land that can be improved through drainage, but the largest areas of wet land are in the eastern half of the country. A large total acreage that could be drained lies in the Southeast, in creek and river bottoms and along the Atlantic coast. The Mississippi Valley has additional thousands of alluvial acres, which can be improved for farming as needed. In the Lake States and the Corn Belt there is still much potentially good land that could be put in better shape for the plow by drainage.

An estimated 20 million acres of fertile undeveloped land needs to be drained if farmland is to be developed from it. Roughly 7 million acres of this drainable land is found in the fertile bottomlands of the Mississippi River, in Arkansas, Louisiana, and Mississippi. Another 7 million to 8 million acres are scattered in the Coastal Plains and other parts of the Southeast. But if this acreage were shown on the map, the dark, dotted space would be increased about a fifth; in the Southeast it probably would be more than doubled. Not all wet land is suitable for drainage. At least 75 million

Types of Tile Drainage Systems

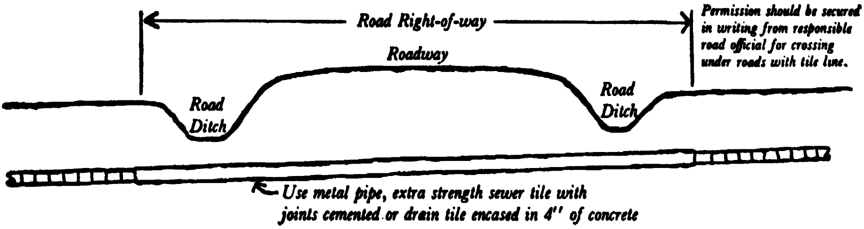




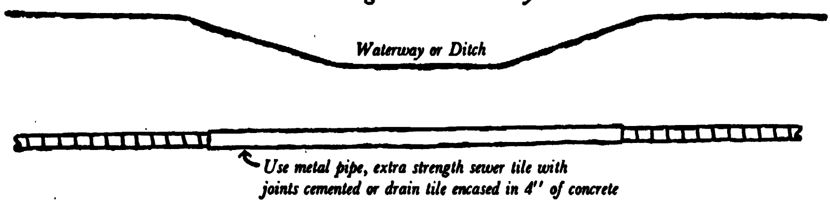


Tile Line Crossings and Handling Shallow Tile Outlets

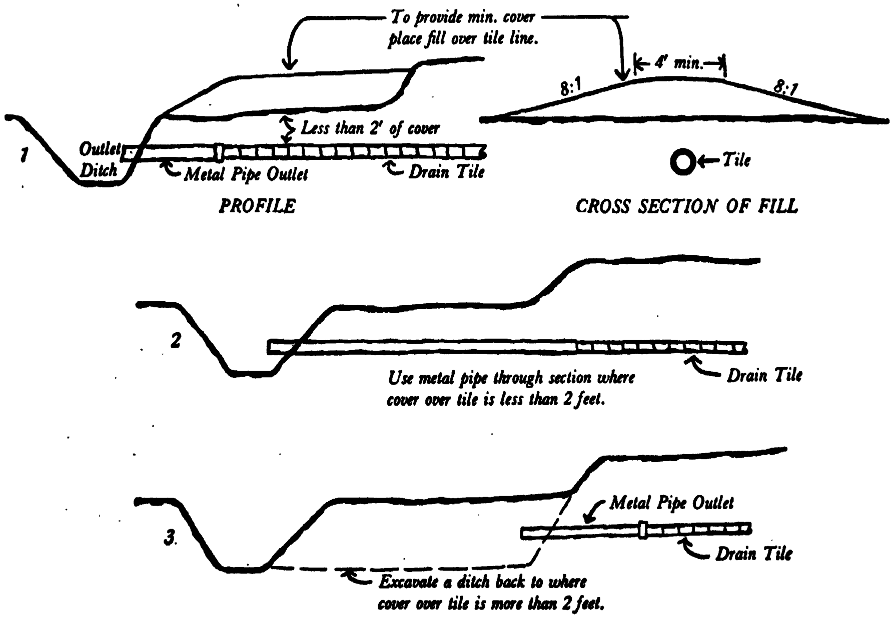
Tile Line Crossing Under Road



Tile Line Crossing Under Waterway or Ditch



Methods for Handling Shallow Depths at Tile Outlet



acres of wet land in the United States are unsuited for agriculture under present conditions, but they can be used for wildlife, forests, and recreation.

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Technical Problems and Principles of Drainage

T. W. Edminster and J. van Schilfgaarde

Excess water becomes a problem when it interferes with tillage, land preparation, the development of plants, and harvest operations.

Much of the excess water is removed naturally by surface runoff, deep seepage, evaporation, and transpiration, but those processes often are too slow to prevent damage to the crop, and farmers must resort to drainage to remove the water faster.

We define agricultural drainage as the removal by artificial means of excess water from the soil profile to enhance agricultural production—more specifically, the removal of excess gravitational water from the soil. The word excess implies that drainage water cannot be considered as water lost, for it never was available for plant growth. The word gravitational indicates that drainage water is not held in the soil by any forces except gravity.

Surface drainage systems are designed primarily to remove water that is on the surface and has not entered the soil profile. That is done by developing the slope of the land so that the excess water will flow by gravity to a system of shallow field ditches, which empty into larger mains and extend to a satisfactory point for disposing of the water.

The removal of water that has already entered the soil profile is considered subsurface drainage. Thus open-ditch drainage removes surface water but is classified as subsurface drainage because the ditches affect the movement of ground water to the same degree as mole or tile drains placed at the same depth.

Essentially any one drainage problem must be considered as a combination of surface and subsurface water removal. They are interdependent;

planning for one without concern for the other will result in systems that are inefficient and ineffective. Solution of a drainage problem also depends on the application of modern soil and crop management principles that will maintain soil structure and high fertility.

Drainage requirements, as they affect plant growth and response, are determined by the effects of the excess moisture on aeration (the amount of air in the soil), soil temperature, biological activity, structural stability of the soil, soil chemistry, and the overall problems of land and crop management.

In localities where drainage is a problem, one often sees stunted crops with yellowing leaves in low areas of a field when the soil has become saturated. If the excess water remains for some time, the plants usually die. Such conditions are primarily the result of root damage caused by reduced supplies of oxygen and accumulations of carbon dioxide with the related effects on the soil-plant relations. The adverse effects are not necessarily from the direct presence of the excess water, for crops will not suffer even in total water culture if they can get air.

Soil aeration is a function of the sizes of the soil particles and their arrangement and the degree of saturation, or the soil moisture content. If the larger pores are free of water, so that the moisture level is below field capacity, gas diffusion can proceed satisfactorily. When the profile becomes saturated, however, the rate of diffusion declines.

As decomposition and other biotic activity continue to take place in the soil, the oxygen level drops, and the carbon dioxide level builds up. That rate of change in the gaseous balance speeds up under higher soil temperatures because of the faster rate of biological activity. The effect of temperature explains why winter flooding often is less harmful than summer flooding. For example, studies in New York have shown that winter flooding does little damage to orchards if adequate drainage develops before leaves start transpiration.

The increases in carbon dioxide content and the lowered oxygen content of the soil atmosphere under saturated conditions affect different crops in varying degrees. Wheat is intolerant of low oxygen availability in the soil, but rice increases in its thriftiness when the soil is saturated. The plants that withstand saturation have specialized air-conducting tissues in their stems and roots, which transfer a normal atmosphere back to the root system.

High moisture levels also reduce the uptake of plant nutrients. Restricted root growth limits the volume of soil from which the plant may draw nutrients. Also, when aeration is poor there may accumulate sufficiently high concentrations of reduced iron and manganese to become toxic to the roots. Decomposition of organic matter when aeration is poor may also produce hydrogen sulfide, a gas that is toxic to the roots.

Denitrification also occurs rapidly in saturated soils, apparently because of the competition for nitrogen by the soil micro-organisms that thrive in saturated soil and the reduction in numbers of nitrifying organisms due to the lack of aeration.

Tissues of plants grown in soil that has been maintained near saturation contain less crude protein—indicating that the nitrogen balance in the soil has been upset. The percentages of potassium, magnesium, and chlorine (but not calcium and phosphorus) are lower in grasses from saturated soils.

Poor aeration and a high moisture content, which usually occur together in poorly drained soils, directly affect the occurrence and severity of some plant diseases. The changes in balance between oxygen and carbon dioxide affect the growth and longevity of the disease organisms. Plants weakened by the soil conditions are also more susceptible to infection. Black root rot of strawberries, cereal root rots, and the fusarium root rots of sugar beets are examples.

Soil temperature, which depends on

many factors, such as the amount and type of radiation received from the sun, the exposure, degree of shade, and the moisture content of the soil, is closely related to the rate of soil moisture movement and retention. The temperature also affects the rate of absorption of mineral nutrients and water by plants, germination, emergence of seedlings, the dormancy period in plants, and the rate of after ripening of seeds. Low soil temperatures restrict root development, usually causing them to grow coarsely, with little branching and few fine roots, and depress the biotic activity in the soil, so that the rate of production of available nitrogen is lowered.

Wet soils are slow to warm up under a given amount of heat input. The heat required to raise 1 pound of water 1 degree would produce a similar temperature rise in about 5 pounds of dry mineral soil or 4 pounds of organic soil. This high heat capacity of the excess water in a soil is the reason that in one study it was found that the heat input used during a 24-hour period to evaporate water from a saturated soil would have raised the temperature of the surface foot of a similar soil at an optimum moisture level approximately 24 degrees. The effect that drainage has on spring warmup of soils and on the related soil temperature conditions, as they affect crop growth, is thus apparent.

SOIL STRUCTURE—the arrangement of soil particles—is affected by frequent or prolonged saturation. The poor structure found under such conditions may be attributed mostly to the lack of biotic activity, reduced root activity, and the lack of drying and wetting cycles. A distinct structural improvement has been noted as drainage has gone into effect. Soil structure, or tilth, often is destroyed when tillage or harvest operations are carried out when the soil is too wet. Drainage helps to eliminate this hazard.

The management of alkali soils and reclamation of inundated lands depends largely on development of adequate drainage through the soil profile to permit the rapid downward or leaching movement of the accumulated salts. Drainage must also be adequate to control the level of the water table so that there will be no danger of salts concentrating in the root zone because of the upward movement of salts from saline ground water. Thus the drainage system must be designed to hold the water table at a safe depth below the root zone and be adequate to remove from the soil profile the amount of water that must pass through the soil profile to leach out the salts added by irrigation, or inundation, plus any other accumulated salts in the soil.

Other important and practical aspects of drainage include the lengthening of the growing season by permitting earlier tillage and planting dates and the elimination of costly delays in machine operations, such as tillage and harvesting, because of wet areas in the field.

IN LAYING OUT a drainage system, two factors must be taken into account. The first is the translation of the problems of soils and agronomy into specific drainage requirements, such as rate of lowering the water table; depth of the water table below the surface; and the degree, length, and frequency of fluctuations in the water table level. The second is the problem of determining the significance of measurements of the position of the water table as an indicator of the status of drainage in the soil profile.

The position of the water table can be determined most easily by augering out an observation well to some depth below the water table. The height to which the water will rise in the well represents the point of atmospheric pressure and thus the location of the water table. Because of the simplicity of its determination in the field and also because of the simplifications that result in theoretical analysis, the water table has been used generally as the

drainage criterion. The region immediately above the water table is still so near saturation, however, that there the soil is still inadequately drained.

The extent of that layer above the water table and its degree of wetness depend on the number and the sizes of the pores in the soil as well as on its moisture history—that is, whether the soil is drying out or being wetted. Thus the water table actually is a poor indicator of the status of drainage.

The soil system through which drainage water flows may be considered to be a series of small, interconnected channels, through which the water moves under the force of gravity and despite the frictional forces developed by the channel sides.

The rate of water movement is proportional to the driving force and inversely proportional to the length of path and the resistance to flow exerted by the soil. The relationship may aptly be illustrated with a permeameter, which consists of a core of soil of height L, placed in a cylinder so that a layer of water of constant thickness t can be put on it. The bottom drains freely into a tube, which discharges into the air at a height H below the free water surface. The rate of flow Q through the apparatus is proportional to the height H, which represents the magnitude of the driving force and the cross-sectional area a, and inversely proportional to the sample height L. The dependence on H can easily be demonstrated by changing the thickness t, or by adjusting the height of the discharge tube, and measuring the resulting rate of flow. This height H is called the hydraulic head, since it represents the head or height of water which tends to push the water through the soil.

The relationship is known as Darcy's law and in formula form can be given as

$$Q=KaH/L$$

or, in a form more useful in many cases, as

$$v=KH/L.$$

We have introduced two new symbols in the equations. K is called the hydraulic conductivity of the soil and represents a measure of the amount of resistance to flow developed by the soil. The symbol v stands for velocity of flow or the rate of discharge per unit of area. Thus $Q=av$.

If two small-diameter pipes are driven into the soil and the soil inside the pipes is augered out, the difference in the heights to which the water will rise in them represents the driving force, or hydraulic head, which causes movement from the endpoint of one pipe to that of the other. The distance between their endpoints corresponds to L in Darcy's law; and if the conductivity is known, the velocity of water between the two points can be calculated.

Besides Darcy's law, the flow of water through soils must satisfy the law of conservation of matter, which is that the total mass of water that leaves a saturated small volume of soil during any time interval must equal the mass that enters the volume during the same period. Since water is incompressible, we may read "volume of water" for "mass of water" in the above statement. The combination of Darcy's law with the conservation law results in a relatively simple mathematical expression, the Laplace equation, which forms the basis of most theoretical drainage work. If the hydraulic head is known at a sufficient number of points (such as along the free water surface and along the drains), the value of the hydraulic head, and therefore of velocity, at any arbitrary point within the soil, in theory, can be calculated by means of the equation. From this velocity distribution, the effectiveness of the drainage system can be evaluated.

All of the exact solutions to specific drainage problems are based on some application of the Laplace equation. It gives a skilled mathematician a good tool, but its manipulation is not simple.

Only two soil properties enter explicitly into the mathematical treatment of drainage problems: Hydraulic conductivity, K, and the porosity.

The hydraulic conductivity, as we

mentioned, often is defined as the constant K in Darcy's Law and can be measured in the laboratory with a permeameter. It is a property of the soil and also of the fluid that moves through it and of the degree of saturation with this fluid. The permeameter measures the saturated conductivity only; more elaborate equipment is necessary to determine its value at other degrees of saturation.

When the analysis is restricted to flow below the water table, a measure of the saturated hydraulic conductivity is sufficient. However, it is well known that a considerable portion of the flow of water towards drainage facilities takes place above the water table through the region called the capillary fringe. To evaluate this portion of the total flow, the relation of hydraulic conductivity to degree of saturation must be known.

The porosity, or rather the volume of pores drained at varying tensions, determines the degree of saturation at any given height above the water table and consequently the hydraulic conductivity in the capillary fringe. The porosity also is of importance when one deals with a moving water table. The water yield, in the case of a falling water table, or the amount absorbed, in the case of a rising water table, depends on the volume of the pores drained. For simplicity, it is often assumed that the pores drained at a tension of 50 or 60 centimeters are instantaneously drained or filled when the water table moves past. But that assumption is but a poor approximation; actually the percentage of pores drained varies continuously with the tension and thus with the height above the water table. Although the 50-centimeter figure may be accurate enough to determine water yield, it is obviously of little value in assessing the contribution of the capillary fringe to the drainage rate.

Furthermore, a mathematical analysis must assume that the soil properties are uniformly constant throughout the region of interest, or at least that they vary in a regular fashion which can be expressed in equation form. Obviously, no soil satisfies this condition so that any mathematical solution can only serve as an approximation.

One of the first uses of the Laplace equation in drainage problems was based on the similarity between flow of electricity through an electric conductor and flow of water through a porous medium. This analogy may be visualized by comparison of Ohm's law, $I=E/R$, with Darcy's law, $Q=av=aKH/L$. The current, I, in an electrical system may be compared to the rate of flow, Q, in a hydraulic system, which in turn is equivalent to the product av of the cross-sectional area and the velocity. The electrical resistance, R, corresponds to the hydraulic resistance, L/Ka; the voltage, E, to the driving force, H. Using this analogy, an electric model can be built and tested corresponding to a hydraulic situation of interest in drainage and the results interpreted in terms of waterflow rather than electric current.

This method, known as the electric analog method, has yielded a series of solutions to problems involving the equilibrium shape of the water table above parallel tile drains attained at a constant rate of rainfall for different values of the hydraulic conductivity, drain size and spacing, depth to an impermeable layer, and so on. It also has been used to study the effect of the width of crack between adjacent tiles and even to follow the downward movement of the water table from an equilibrium position when rainfall stops.

A shortcoming of the method is that one must assume that the drains run under pressure or at least run full. Such a condition should never occur in a well designed drainage system, but it is required for the analog to be valid. Another disadvantage of the method is that a separate solution must be found for each case, whereas a mathematical attack generally yields a solution that applies to a series of problems.

THE MATHEMATICAL APPROACH is conveniently discussed in two parts. First, there are those cases that are independent of time. They include such conditions as a constant rate of rainfall or a soil with water ponded on the surface. They are called steady state problems.

The second class involves nonsteady problems, such as a falling or a rising water table.

The same principles apply to both steady and nonsteady state problems. The distribution of hydraulic head through the whole flow region is determined by the Laplace equation if the conditions along the boundaries of this region can be specified. In the steady state case, the boundary conditions remain constant with time; in the nonsteady state case, they vary with time.

One of the simplest steady state problems involves the flow of water towards a vertical, cylindrical well through a saturated, permeable stratum bounded above and below by an impermeable layer. The distribution of hydraulic head for this case is given by $H=C \log r$, where C is a constant depending on the hydraulic conductivity and the conditions in the well, and $\log r$ represents the logarithm of the distance, r, of any point to the center of the well. A number of tile drainage problems can be analyzed by application of this well equation.

This method of analysis permits finding the hydraulic head distribution for a single drain placed in a homogeneous soil which is saturated to the surface. This same process may be extended to yield solutions for hydraulic head distributions for a series of parallel drains, or for one or more drains overlying an impermeable layer. Although the actual technique becomes more difficult and tedious, the principle remains the the same. This method can only yield exact solutions for cases where the water table is flat.

THE HODOGRAPH METHOD is another approach that has successfully been applied to steady state problems. It utilizes the hodograph plane, which is a plot of the velocity along the boundaries of the flow region connected with a drainage system on a plane with the horizontal and vertical velocity components as axes. The method involves plotting the flow region on the hodograph plane and then matching the original flow region with its hodograph counterpart through a series of conformal transformations, finding the hydraulic head distribution in the process. The process requires considerable skill and has only been applied to a limited number of cases. It has yielded, however, a general solution for the position of the water table under equilibrium conditions over a series of parallel tile drains in a homogeneous soil for constant rates of rainfall and deep seepage. The solution also applies to a constant rate of evapotranspiration, instead of rainfall, and to artesian upward movement in place of deep seepage.

THE RELAXATION METHOD is the third method that has resulted in important steady state solutions. In principle, it is simply a trial-and-error determination of the value of the hydraulic head at the intersection points of a grid placed on the flow region. The method requires large amounts of labor, although a technique has been developed that reduces the time required considerably. It enables the solution, however, of numerous problems with any specified degree of accuracy.

Three methods used to obtain exact solutions of steady state problems have been briefly described and, by all three of these, important knowledge concerning the behavior of drainage systems has been obtained. However, they also suffer from the same limitations. First, steady state conditions never are found in the field, although conditions found in some humid regions may approach a steady state. Secondly, just as with the electric analog, the applications are restricted to cases where the drains run full. Therefore the hodograph solution for steady rainfall also has been found to

apply exactly only to rainfall rates and conductivity values that are outside the range of practical importance. It yields good approximate solutions for practical cases, however. Thirdly, the analyses assume uniform soil conditions, although homogeneity is the exception rather than the rule in the field. Finally, the form of most of the exact solutions is such that they do not lend themselves readily to daily use by practicing engineers.

In view of the objections that have been raised, there appears justification for the use of simpler, approximate solutions in a number of cases. The most widely used approximate solution probably is the ellipse equation. This equation, derived on the assumptions that all flow is horizontal and that the velocity of flow is proportional to the slope of the water table, does not satisfy either the mass conservation law or Darcy's law. If its use is restricted to conditions where an impermeable layer is found at a shallow depth below the drains, and if it is used only to determine the height of the water table midway between drains rather than the shape of the water table, it has been found to yield surprisingly accurate results. The danger in using the equation lies in a lack of appreciation of its limitations. For those instances where the impermeable layer is nonexistent or is not near the drains, a simple approximate solution has been found based on the well equation mentioned earlier. For intermediate cases, a scheme of combining the two has been developed. If good judgment is exercised, these simple solutions are quite valuable, but their approximate nature must always be kept in mind.

THE DEVELOPMENT of nonsteady state solutions has met with far less success. The inclusion of time as a variable complicates the analyses greatly.

It has been shown that the relaxation method can be extended from steady to nonsteady state applications by considering transient cases as a series of successive states independent of time. This approach in theory enables the solution of numerous special cases with any desired accuracy, but the method is so tedious that the expense involved greatly limits its practical value.

All other solutions that have been proposed are of an approximate nature. Assumptions similar to those leading to the ellipse equation lead to an equation often referred to as the heat flow equation instead of the Laplace equation. Solutions based on it have the serious shortcomings that they do not take into account the effect of convergence of flow into tile drains and that they can only be used when an impermeable layer occurs near the drains. Still it appears that such solutions are the best available at present.

Some other solutions have been proposed based on the assumption of radial flow, which states that all water flows linearly toward the drains. They yield such inaccurate results that it is doubtful that they have much value.

THE RELATIONSHIP between investigations and practical field problems in drainage design is sometimes difficult to visualize. It is often suggested that all research in the field of drainage should be directed towards field experimentation. If this were done, however, one would lose many of the vital foundations upon which successful field studies may be developed.

For example, a primary problem in drainage design is the determination of the proper depth and spacing of drains. Although that problem has evaded solution in much of the United States, the practice in western Europe is to calculate depth and spacing from field measurements of the hydraulic conductivity, using the approximate steady state solutions just discussed. The uneven rainfall, coupled with the variable soil conditions found in this country, are the cause of the difficulties encountered here. It is expected, however, that as methods of measuring and evaluating these soil and rainfall variables become known, the theoretical

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solutions to the water movement problems will be of prime importance.

Interception drainage and drainage of highly stratified soils having layers of widely varying conductivity have presented many problems for field engineers. While field studies gave clues to the proper placing of tiles under such conditions, it was not until a detailed theoretical analysis was applied that these problems were fully understood.

The effect of width of crack space upon drain-tile efficiency is a widely disputed question in the field. Through a combined approach of theoretical computation and field measurement, evidence was gained that doubling the width of crack between adjacent tiles increases the rate of flow into the drains by about 10 percent. Thus, drain tile spaced one-sixty-fourths inch apart, a normal spacing when even-faced tiles are put close together, will remove about 30 percent less water in a given period of time than tile spaced one-eighth inch apart when the soil is fully saturated.

The combination of theoretical analysis with field studies has also made possible valuable contributions in evaluating the effect of the size of drains, the effect of gravel envelopes around drains, and the effect of artesian pressure on drain spacing. In each instance the theoretical studies have contributed much to the understanding and applicability of field experimentation findings.

In this discussion emphasis has been placed on the search for a theoretical foundation upon which field design of drainage facilities can be based. In the scientific approach to any problem this is of first importance. It is recognized that drainage design will never become an exact science; it will always require sound judgment based on local experience. The heterogeneity of the soil, the nature of climatic fluctuations, and changes in economic conditions rule out the possibility of a completely rationalized scheme. An understanding of the basic principles, however, can help the field technician in making a more logical and reliable evaluation of the factors involved.

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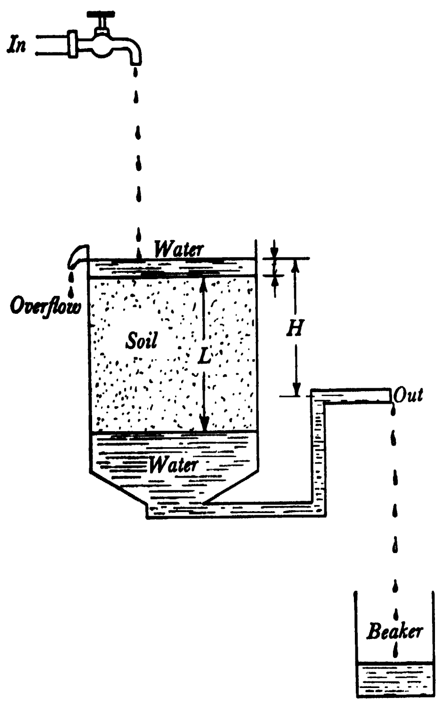


A permeameter.

Systems for Draining the Surface

K. V. Stewart, Jr., and I. L. Saveson

Surface drainage is used to remove excess rain in flat places where the water moves too slowly through the soil to provide adequate drainage. The force of gravity moves the water in orderly overland flows.

The need for drainage depends on the slope and smoothness of the surface. Flatness—the lack of slope—means that the excess water may move too slowly.

Depressions and barriers—the lack of smoothness—mean that the excess water will be impounded. Impounded water becomes stagnant, because it is removed only by infiltration into the soil or evaporation, both of which might be very slow processes.

The topography of farmland varies mostly because of natural geological processes. Most delta farmlands have scars of flood flows, such as sloughs, depressions, and irregular surfaces that are due to the unequal distribution of water-transported materials. In the northern part of the United States the variations can be attributed to glacial influence. Deposits left by the melting ice cake caused many depressions and barriers on the land surface.

Another cause of a pocketed surface is the failure to smooth the field after tillage to remove scars made by farm implements. Often the breaking and cultivating of farmland in the same direction season after season leave holes where the implements enter the ground and pile up earth where they leave the ground. The inadequate disposition of spoil banks from ditch excavation, both outlet and field drains, has left many barriers which cause ponding. The presence of ponded water after heavy rains indicates an unsmooth surface.

Research studies conducted at the Agricultural Experiment Station of Louisiana on the grading of sugarcane land to improve drainage demonstrated the relationship between the number and area of water-ponding pockets and yields. Smooth fields produced 4.59 tons of cane more than did land 53 percent of whose surface was ponded 2 inches and more.

Proper planning should produce a drainage system that will permit maximum effective water intake and storage in the soil and will remove excess rain without excessive erosion, so that pasture, hay, and row crops have the best possible moisture conditions.

There are two ways to remove the water from unsmooth, pocketed land in order to get adequate surface drainage. One way is to install enough field ditches to drain each individual pocket. The other is to grade and smooth the land.

Often an undue amount of field ditching would be needed to drain every pocket. Besides, a considerable acreage would be taken out of cultivation, the expenses of maintaining the ditches would rise, and farm operations would be made more complicated.

Therefore the more logical way is to grade and smooth the land to provide a surface that will not interfere with the movement, removal, and distribution of surface water and after doing that to install enough field drains and lateral ditches to move excess rain to the outlet drains.

Many farm surface drainage systems function as combination diversion and drainage systems. Runoff from higher lands is diverted to downslope ditches and carried to the drainage outlet. That keeps the excess water from accumulating in the lower areas and permits the removal of the runoff from all parts of the field at a reasonably uniform rate.

On small farms and on some fields where an adequate outlet is readily accessible, the drainage system can be relatively simple. Simplicity and adequacy are the goals of good farm drainage.

The type of surface drainage system to be installed depends on the topography, the types of soil, the likes and dislikes of the farmer, the type of farming, the kinds of farming equipment in use, the farm road system, and the methods to be used to maintain the ditches.

A farmer who is planning a drainage system should give thought to a complete system that will provide continuous drainageways from the farthest individual plants in the crop rows or depression to the drainage outlet.

SURFACE farm-drainage ditches usually consist of field drains, which collect the water from the crop rows or the land surface and remove it to lateral or collecting ditches, thence into main ditches, and thence into the natural or artificial watercourse that carries the water away.

The term field drain, as we use it, means a shallow surface ditch with flat side slopes, which can be crossed with tillage implements. It is usually designated as a single field drain, if only one ditch is indicated, and as a double field drain, W-ditch, or twin ditch, if two single, parallel field drains are located near each other.

The single field drain is used if the material excavated from the drain can be placed on the lower side so that it will not obstruct row drainage or entrance of surface water. It is also used in places where excavated material is placed in nearby depressions.

The double field drain is used in places where row or surface water enters from both sides and the excavated material is not used to fill depressions. The excavated material is usually placed between these field drains and shaped to permit farming and crossing with tillage implements.

Normally field drains are 9 to 12 inches deep, with a maximum depth of 18 inches. Side slopes have a minimum ratio of 4 to 1—preferably 6 to 1, or even flatter.

The spacing of field drains must take into account the soils and the topography. If the topography is undulating, the location is more or less dictated. If the surface is uniform, the spacing is determined by soil types. A common practice is to space the field drains about 400 feet apart on the heavier (clay) soils and about 1,000 feet apart on the lighter (sandy) soils.

Lateral, or collecting, ditches collect the water from the field drains and transmit it to the main farm ditches. Ordinarily they are deeper than the field drains—usually 1 foot or more. Generally they have flat side slopes to facilitate crossing with farm equipment, mowing, and maintenance. In some sections of the country, however, they are of a box type, with steep side slopes. In some soils, steep ditch banks are more stable than in other soils.

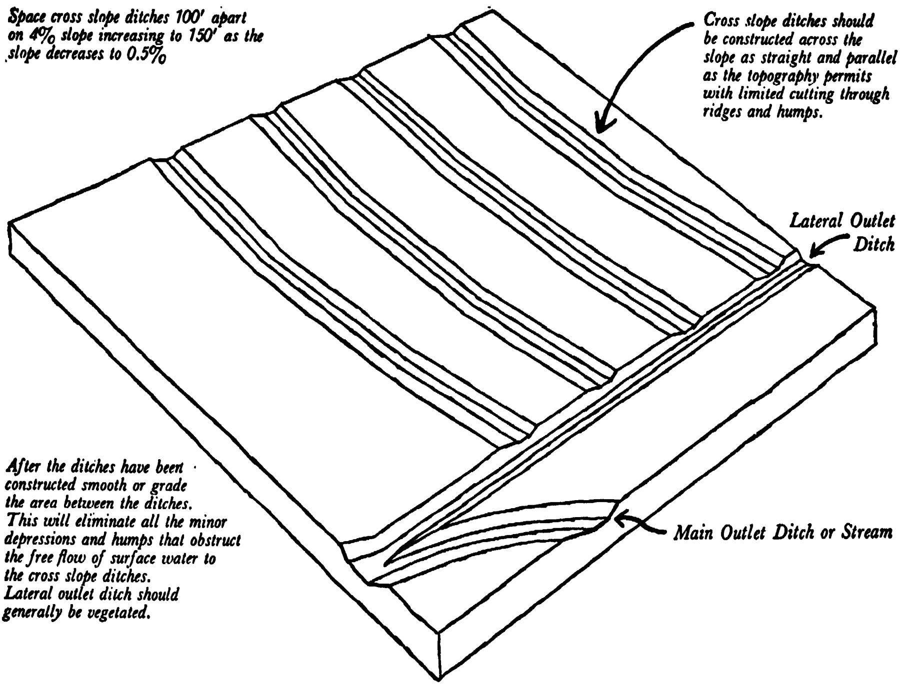
Main ditches collect the water from lateral ditches and transport it to the natural or artificial drainage outlet. The main ditches generally are constructed with draglines and usually require considerable planning and supervision by engineers if they are to function properly.

No fixed rule can be given for each ditch location. Every field is an individual problem. Usually the main ditches are located in the natural depressions. If natural depressions do not exist or are too far apart, ditches are located at intervals according to topography, soil characteristics, farm boundaries, roads, and other physical features.

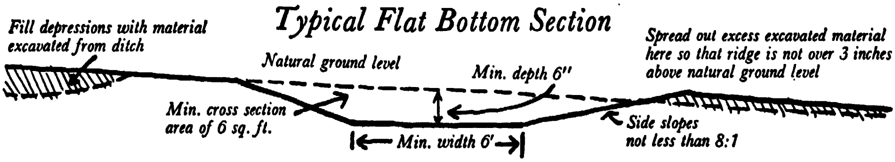
Proper alinement of ditches is important. Consideration should be given to keeping straight ditch sections as long as practical, with gradual curves between straight sections to permit maximum hydraulic efficiency. Ditches should be straight when topography and field conditions permit. It is well to have ditches parallel to each other so that there will be no point rows. Ditches should not be located in such a way as to create small, inaccessible corners in the field.

Usually the ditch system consists of field drains, lateral ditches, main ditches, and drainage outlets.

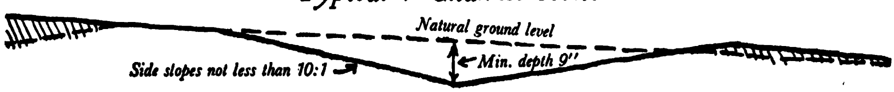
Cross Slope Ditch System of Surface Drainage— Terrace Type Drainage



Typical Flat Bottom Section



Typical V-Channel Section



The type of drainage system used is determined by the topography, the type of farming, and the kinds of crops grown.

THE REGULAR OR PARALLEL system is used in places where the surface is uniform and has few noticeable ridges or depressions. The system may be planned so that ditches will be at right angles to the field drains and uniformly spaced. That is called the regular or parallel system. It is the most desirable surface-drainage method, as it squares up with the field and eliminates most point rows or short rows. It is well adapted to the use of four-row farm machines.

An adequate study of fields formerly considered unadapted to the regular system often will disclose the possibility of adapting most of its desirable features. An example is the use of parallel lateral ditches, with most of the field drains at right angles but with some of them located in shallow depressions, which meander from one lateral to another.

THE RANDOM SYSTEM is used in places where the ground surface is broken by a series of ridges and depressions—an undulating land surface. In a random system, the location of the lateral ditches is dictated by the topography. It is often necessary to install one or more additional lateral ditches between the natural depressions if the distances are too great to drain well.

THE BEDDING SYSTEM is widely used in pastures, hayfields, and row-crop fields. It is adapted to fields with very little slope, usually 0.5 percent or less, with slowly permeable soils. It has a series of parallel lands, or beds. The surface is shaped and smoothed so that runoff drains laterally from the lands, or beds, into dead furrows, thence into cross-slope collection ditches, and finally into the main outlet ditch.

It is desirable to lay out the beds with the dead furrows running in the direction of greatest slope. As the collection ditches can be excavated to grade, they are located approximately perpendicular to the slope.

It is usually unprofitable to grow row crops in dead furrows. The widths of the beds are planned to fit the row widths and the types of farming equipment to be used so as to avoid unnecessary loss of ground and a crowding of the rows next to the dead furrows.

If this system is to function satisfactorily, all dead furrows must have a continuous grade, with no high or low points that would interfere with adequate drainage. The beds, or lands, should be shaped and smoothed so there are no depressions to hold water.

THE CROSS SLOPE system of ditches resembles terracing. Field drains are constructed around the slope on a uniform nonerosive grade. The method is adapted to fields that have poor internal drainage from the plow depth downward and have many shallow depressions and usually make it unwise to use the bedding system.

The field drains are constructed as straight and parallel as topography permits, with limited cutting through low ridges. Ordinarily field drains are spaced 100 to 150 feet apart.

Material excavated from the field drains is placed in the lower places. Excess material is spread near and just below the lower side of the field drains, so that the resulting ridges are not more than 3 inches above the normal ground surface. The area between the field drains is graded and smoothed to permit free flow of water.

Rows are laid off approximately perpendicular to the field drains if the slopes are so flat they will not erode.

THE FIELD DITCH system as a rule employs the regular cross slope system. The ditches are deeper than those used in other surface methods and therefore provide drainage for both surface and subsurface water.

This system is adapted to the more permeable soils. It may be used on peat and muck soils that cannot be tiled and

on deep sands and other moderately or highly permeable soils that have a high water table. Because of the depth of the ditches, they are seldom crossed with farm machinery. Filling of low areas with excavated material and grading and smoothing of the land are recommended.

Ordinarily the rows are laid off parallel with the ditches. Field drains should be used to carry row water to the ditches, with outlet or overfall protection provided.

THE SUGARCANE system has been in use in the sugarcane area of Louisiana for a century. Lateral ditches, known as split ditches, are constructed with the general slope of the land and are usually parallel. The spacing varies from 100 to 250 feet. The ditches are 18 to 36 inches deep. They are about 4 feet wide at the top and 2 feet wide at the bottom.

If the topography permits, split ditches usually are extended to a point where the runoff from the field equals the ditch capacity. They are intercepted at that point by a cross ditch.

Cane rows are usually 12 to 18 inches high and 6 feet wide. Rows are laid off parallel to the split ditches.

Water from the rows is carried by small cross drains, or quarter drains, to the split ditches. Quarter drains are usually located next to field roads or turn rows and in shallow depressions. A quarter drain is a small field drain, usually straight, constructed across the rows with a plow or similar farm implement. A shovel is usually used to remove the earth thrown into the row middle. The main ditches are large excavated ditches leading to swamps, streams, or drainage outlet canals.

THE RICE DRAINAGE SYSTEM functions primarily to remove rainfall in excess of that required to flood the field. Adequate drainage is required during periods of seedbed preparation and harvest and during alternate years when the field is fallow. It also is used for pasture or row crops.

The rice drainage system on the average farm consists of main and lateral ditches and quarter drains.

THE DESIGN of surface drainage systems should take into account the capability of the land to be drained.

Maps showing land capability are available at Soil Conservation Service offices in many county seats.

Characteristics and properties of soils have an important bearing upon the design and the construction of surface ditches. Enough soil borings should be taken along proposed ditch locations to determine the proper side slopes and depths, especially if the ditches are to be more than 6 feet deep.

The following information should be known before a surface drainage system is designed: Size and nature of the drainage area; how much runoff must be carried; length of time permitted to remove runoff; kinds of crops to be grown; conditions of the soil through which the ditches must be excavated; land grades along the ditch location; suitability of the drainage outlet; and the smoothness of the land.

Probably the worst drainage problems are encountered on bottom lands next to eroding hills. Soil washed down from hills contributes silt to ditches and low lands. Such lands should not be drained until the erosion has been stopped by soil-conservation practices.

MOST DRAINAGE ENGINEERS or organizations conducting drainage operations use runoff curves developed for the locality. Rainfall, topography, soils, and crops are considered. Removal rates vary according to crop needs and local conditions.

The condition of the outlet for the farm discharge system should be investigated to determine that it is adequate for drainage.

In many localities it is customary to plot the planned surface of the water in the ditch as a profile, beginning at the outlet and proceeding upstream. The plotted profile represents the energy gradient, which produces ve-

locity, and also the elevation of the water surface for most low-velocity drainage ditches. It is known as the hydraulic gradient, or gradeline.

The hydraulic gradient is kept as near the ground surface as conditions permit, but at or slightly lower than the elevation of the main areas to be drained. Exceptions are deep ditches for subsurface or water-table control where more depth is required.

It may not be possible or practical to give adequate drainage to all small areas. Sometimes it may be more economical to fill them with excavated material.

It is good practice to keep the hydraulic gradient constant or increasing in a downstream direction—that is, resulting velocities are constant or increasing, but it may not always be possible to do so because of topography, soils, or costs.

CROSS SECTIONS OF ditches should be designed in accordance with the proposed maintenance methods, the construction equipment to be used, and the characteristics of the soil. Ditches should be designed for the most efficient section in terms of carrying capacity, but with soils, practicability of construction, and maintenance in mind. Ditches in clays and clay loams have functioned satisfactorily with 1.5:1 side slopes. Slopes 0.5:1 or flatter are used on loessial silts or silt loams.

Ditches less than 4 feet deep in sandy loam bottom-land soils usually have 2.5:1 or 3:1 side slopes. Nearly vertical slopes have stood up well on peat and muck soils.

Deep ditches to be maintained by grazing should have side slopes flat enough for cattle to climb—2:1 or flatter.

The equipment to be used to maintain the ditches by burning or chemical sprays should be considered in designing. Slopes as steep as 0.5:1 are sometimes used.

The dragline has been used for excavating drainage ditches. It is favored because it can remain on solid footing away from the channel to be excavated.

Ditches to be constructed with dragline equipment should have bottom widths as wide or wider than the dragline bucket. V-bottom ditches can also be cut with dragline equipment.

Lateral ditches to be cut with pull-grader, motor-grader, or light equipment, and maintained by mowing or grazing, usually have V-bottom design, with side slopes of 3:1 or flatter. Flat bottom ditches are also used.

When excavation is to be done with scrapers, the V section can be used, or the bottom width can be designed as wide as the tread of the scraper. Side slopes of scraper ditches must be flat enough for the scraper to operate on the slope—usually 3:1 or flatter.

In many places it is necessary to drop water from a shallow ditch to a deeper ditch or to drop water from a ditch into a deeper bayou, creek, or drainage outlet. Stabilizing structures often are needed there to control erosion.

Low overfalls in heavy soils, where good protection is afforded by rapid revegetation, may be sloped to a 1-percent grade. Other locations in light and more erosive soils, where native revegetation is slow, may require sodding, seeding, or mechanical structures if the overfall is as little as 1 or 2 feet.

The capacity of a ditch is determined by its cross-sectional area, hydraulic gradient, roughness coefficient, and shape.

The tables give an idea of the capacities of small ditches.

SOLID SPOIL BANKS, spread to form a low ridge on both sides of the main and lateral farm ditches, prevent water from running over the ditch banks at random. The water must then enter the ditch through planned inlets, and trouble from sloughing side slopes, gullying, and the resulting silt deposits in the channel is avoided.

In constructing a drainage system, the spoil banks should be leveled or smoothed to facilitate maintenance of the ditches and to permit use of these otherwise lost areas. Otherwise the

Areas of Level to Gently Rolling Land That Can Be Drained by Small Flat-bottom Ditches with 2-to-1 Side Slopes, Running Full

[Computed by Manning formula, $n=0.045$]

Depth of ditch (feet)	Bottom width of ditch	Top width of ditch	Excavation per 100 feet	Area drained by ditches with fall per 100 feet of— 0.02 foot	0.04 foot	0.06 foot	0.08 foot	0.1 foot	0.15 foot	0.2 foot	0.3 foot	0.4 foot	0.5 foot
	Feet	*Feet*	*Cubic yards*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*
1.5.	4	10	38.9	57	81	100	115	129	157	182	223	258	288
	6	12	50.0	78	110	135	156	174	214	247	302	350	390
2.0.	4	12	59.3	102	145	177	205	229	280	324	397	459	[1] 510
	6	14	74.1	135	191	234	270	301	369	426	525	604	[1] 700
2.5.	4	14	83.3	162	230	282	325	363	445	515	630	[1] 800	[1] 970
	6	16	101.8	209	296	362	419	467	570	675	965	[1] 1,240	.....

[1]Velocity is within range 2.6 to 3.0 feet per second.

From U. S. D. A. Farmers' Bulletin 2046, *Farm Drainage.*

Areas of Level to Gently Rolling Land That Can Be Drained by V-Shaped Field Ditches Running Full

[Computed by Manning formula, $n=0.045$]

Depth of ditch (feet)	Top width of ditch	Side slopes	Excavation per 100 feet	Area drained by ditches with fall per 100 feet of— 0.02 foot	0.04 foot	0.06 foot	0.08 foot	0.1 foot	0.15 foot	0.2 foot	0.3 foot	0.4 foot	0.5 foot
	Feet		*Cubic yards*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*	*Acres*
1.0......	6	3 to	11.1	10	14	17	20	22	28	32	39	45	50
	8	4 to	14.8	13	19	23	27	30	37	43	53	61	68
1.5......	9	3 to	25.0	30	42	52	60	67	82	94	116	134	149
	12	4 to	33.3	40	57	70	81	90	110	127	156	180	202
2.0......	12	3 to	44.5	64	91	111	128	143	176	203	249	287	321
	16	4 to	59.3	87	123	151	174	194	238	275	338	390	436

spoil banks soon grow up in brush and trees, which prevent the use of maintenance equipment.

LAND GRADING and smoothing is one of the more recently developed drainage practices. The land surface is generally formed or graded to provide a smooth surface with the general land slope. Depressions are filled by earth excavated from high areas or from ditches. Before the forming operations, the high and low areas of the field are determined by a topographic survey or are located by marking them after heavy rains.

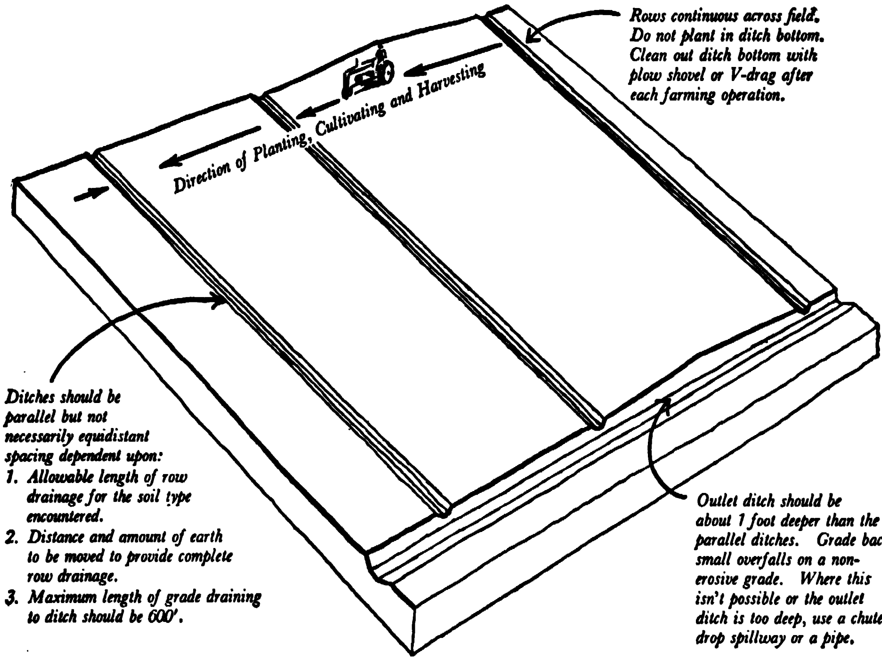
Land grading and forming work is best done by earth-moving equipment, such as wheel scrapers and bulldozers. The bulldozer is adapted to moving earth less than 300 feet. The scraper can transport earth longer distances.

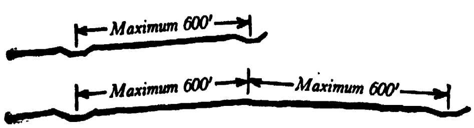
The equipment best adapted to smoothing the land, after it has been formed by grading, is the land leveler, which was developed for use on irrigated land in dry sections. Often it is wrongly considered to be a tool for moving earth. It is a finishing tool, developed to smooth the surface. It corrects small discrepancies in grade beyond the range of heavy earth-moving equipment.

Most areas are graded and formed by earth-moving equipment to within 2 inches or so of the desired grade. The land leveler then finishes the grade within the working length of the machine. The land leveler is a practical, automatic operating machine, which requires a minimum of skill in operation. It can be used also on older graded areas to reduce the implement scars from each cropping cycle.

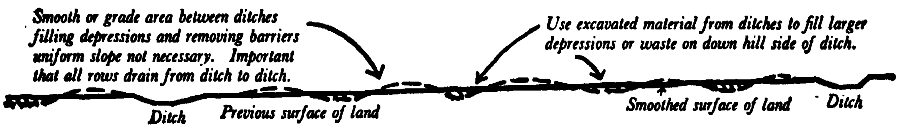
Land levelers are of many types and sizes to meet various types of land and farming conditions. They should be as long as feasible, because length ex-

Parallel Ditch System of Surface Drainage

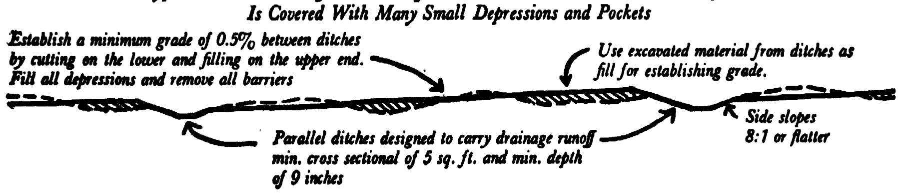




Typical Cross Section of Ground Surface That Has Some General Slope in One Direction and Is Covered With Many Small Depressions and Pockets



Typical Cross Section of Ground Surface That Has Little or no General Slope and Is Covered With Many Small Depressions and Pockets



tends the smoothing, or planing, influence over a longer area. Size of field and available power also are factors.

Field trials in many sections disclosed substantial increases in yields on graded and smoothed land. Graded and smoothed test areas in Louisiana averaged 5.81 tons of sugarcane to the acre more than an ungraded check area in the first cycle of sugarcane. The second cycle continued to show an increase over the check area. In many instances the cost of grading sugarcane land was liquidated by the increase in yields the first year, and the increase in yield the following year was net profit. Planters also reported that farm implements operate more easily and efficiently on the graded and smoothed land.

According to Agriculture Handbook No. 61, *A Manual on Conservation of Soil and Water*, of the Department of Agriculture, ditching with dynamite is possible under almost any condition. Usually it is economical for constructing small ditches or cutoffs in stream channels, in soils other than gravel and dry sand. Dynamiting is best suited for ditching in soft ground where heavy machinery would bog down and in places where the amount of earth to be moved is too small to pay for a power-excavating machine. A saturated sedimentary soil that is firm but not stiff and free from stumps and large roots is suited to ditching by dynamite. Manufacturers of explosives can give detailed directions for loading and firing explosives in ditching and for handling and storing dynamite.

PROPER AND FREQUENT maintenance is required if drainage systems are to continue to work well.

One method of maintenance involves the removal or control of vegetative growth. Grazing by livestock, except hogs, is effective, but grazing usually has to be supplemented by mowing (or hand methods) to control undesirable grasses, weeds, and brush.

Often it is impractical to fence ditches in row-crop fields. There the ditches should have flat side slopes to permit mowing. Mowing is good practice: In Louisiana many regularly mowed ditches function well after 8 years of no other maintenance than mowing.

Vegetation also can be controlled by flamethrowers.

Chemicals—among them 2,4-D and 2,4,5-T—to kill vegetation in ditches are used more and more on the larger systems but to a lesser extent on farm drainage systems because the spray might drift to crop fields and harm them.

In some places where willow and cottonwood are troublesome, the seedlings are pulled by hand—an expensive practice, but sometimes the only means of control.

The removal of fallen trees, drift, silt bars, and other debris that accumulates in ditches is necessary if efficient operating conditions are maintained.

Proper and adequate maintenance generally depends on regular inspections. One should inspect the system immediately after heavy rains to see that bridges, culverts, water gates, ditch intersections, and overall locations are still in good order.

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Tile Drainage—Its Installation and Upkeep

Keith H. Beauchamp

Tile drainage removes excess water from the soil through a continuous line of tile laid at a specified depth and grade. Free water enters through the tile joints and flows out by gravity, so that the water table is lowered below the root zone of the plants.

Lateral drains remove the free water from the soil. Submains collect the water from a group of laterals. A main carries the tile water from the submains and laterals to the outlet.

Tile drains, properly planned and installed, become a permanent improvement that needs little maintenance. Care must enter the planning and construction so that the best and most economical system is installed—particularly because the tile are hidden and causes of failure are hard to find and costly to repair.

AN ACCURATE SURVEY of the field to be tiled is generally needed to plan the most efficient layout of laterals and mains. The survey should determine the grade of the main so that the size of tile will be correct for the area to be drained. The tile system should be planned to handle all of the wet area that could eventually be drained into one main even if only part of the area is to be tiled at first.

A system of short mains with long laterals is most economical, because mains require larger and more costly tile. For uniform drainage, laterals should be parallel and the same distance apart. That provides for a uniform water table midway between laterals and allows each line to cover its maximum area. Better drainage generally is accomplished by locating the laterals across the slope rather than up and down. Tile lines should always be placed off to one side of water courses and far enough away to protect them from washing out.

The topography of the land, source of water to be removed, and various other field conditions determine the right location of tile lines and the proper type of drainage systems.

Tile systems can be classified by three general types—a system of parallel lines, a random system, and an intercepting system.

THE PARALLEL LINES systems are used on poorly drained soils having little slope and approximately uniform texture. Variations are the gridiron and parallel systems, the herringbone system, the double main system, and the grouping system.

In the gridiron and parallel systems, one main or submain serves as many laterals as possible. Thus the length and number of outlets are kept to a minimum. The laterals enter the main or submain from one side only. That is the most economical arrangement as the land on only one side of the submain or main is double drained—that is, a narrow strip of land along the main is drained by both the submain and the lateral. The system can be used on land that is uniformly wet if it slopes generally toward the main or submain.

The herringbone system is applicable in places where the main or submain lies in a narrow depression and the laterals must enter from both sides. It is less economical, because considerable double drainage occurs where the laterals and mains join. If the depression over the submain is unusually wet, however, this system will provide better drainage at that point.

The double main system is a modification of the gridiron system. It may be used where the submain is in a broad, flat depression, which frequently is a natural watercourse and sometimes may be wet because of small amounts of seepage water from nearby slopes. A submain on each side of the depression serves the double purpose of intercepting seepage water and providing submains for the lateral. The

double main arrangement also eliminates the need to have any laterals cross under the waterways and thus eliminates the possibility that the lateral will be washed out should the waterway deepen by erosion. A submain on each side of the depression also permits a more uniform lateral grade line without an abrupt break in grade. A submain laid at the foot of each slope makes possible more uniform grades for the laterals, and smaller tiles can be used than would be needed for a single main in the center of the watercourse.

Grouping systems, a combination of individual systems, are useful when topography and wetness on the field vary and the pattern of drainage must be changed to fit the different conditions.

THE RANDOM SYSTEM is used in rolling areas that have scattered wet areas somewhat isolated from each other. Tile lines are laid more or less at random to drain the wet places. In most instances, it is better to locate the main so as to follow natural drainageways rather than to make deep cuts through ridges to make straight tile lines. Submains and laterals should be extended from the main to the individual wet areas. If the wet spots are large, the arrangement of the submain and laterals for each wet place may utilize one or more of the parallel systems to provide the required drainage.

THE INTERCEPTING SYSTEM involves the interception of seepage water that follows the upper surface of an impervious subsoil. It is possible to locate tile so that the seepage water will be intercepted and the wet condition relieved. Proper location of the tile for interception of seepage water is important. The seepage plain must first be located by soil borings or by trenching. The tile line should then be placed approximately at the impervious layer along which the seepage water travels. The tile line should also be located so that there are at least 2 feet of cover over the top of the tile.

THE TILE OUTLET is the starting point in planning a tile drainage system. The system, no matter how carefully installed, will not work properly if the outlet does not function well. Tile drains may outlet by gravity into natural or artificial channels or existing tile mains. Either is suitable if it is deep enough and its capacity is big enough.

An open channel outlet should be large enough to remove the drainage runoff from the watershed quickly to prevent crop damage. It should be deep enough so that when the tile are laid at the proper depth, at least 1 foot of clearance exists between the flowline of a tile outlet and the low-water stage in the channel. That clearance can be reduced if the outlet channel is on such a grade that silting will not occur and if the stream recedes to low-water stage in a few hours after a storm. The clearance should be increased if the outlet is in sandy or organic soils or is subject to rapid filling with sediment.

An existing tile main that is used as the outlet should be in good working condition. It should be deep enough to permit the laterals of the proposed system to be laid at the optimum depth for the soil to be drained. Enough capacity should be available to handle the proposed system. Allowance should be made for surface inlets and possible additional tile lines.

When a gravity outlet, either by open ditch or tile main, is not available or when it is impractical to improve the outlet, the possibilities of providing an outlet for the tile system by pumping should be considered. Pump drainage is described in another chapter.

THE TILE should be big enough to provide capacity to remove a required amount of water from the soil in 24 hours. This rate of water removal that must be handled in order to provide the required degree of protection to the crops is called the drainage coefficient.

To be considered in selecting the drainage coefficient are frequency, intensity, and duration of rainfall; porosity and permeability of the soil; crops

to be grown; and the method of disposal of surface water. Most truck crops require the removal of surplus water within a few hours after a rain and therefore require a higher coefficient than field crops. Where there are surface inlets, the inflow into the tile line is at a greater rate than on lines without inlets, and thus larger tile are required.

The table below gives some recommended drainage coefficients for various crop and soil conditions with and without surface inlets.

Soil	*No surface water admitted to the tile and complete surface drainage provided*	
	Field crops	*Truck crops*
	Inches	*Inches*
Mineral	3/8–1/2	1/2–3/4
Organic	1/2–3/4	3/4–1 1/2

Soil	*Surface water admitted to tile through surface inlets*			
	Blind inlets		*Open inlets*	
	Field crops	*Truck crops*	*Field crops*	*Truck crops*
	Inches	*Inches*	*Inches*	*Inches*
Mineral	1/2–3/4	3/4–1	1/2–1	1–1 1/2
Organic	3/4–1	1 1/2–2	1–1 1/2	2–4

The size of tile needed for required capacity is based on the size of the area to be drained, the grade of the tile line, and the selected drainage coefficient. That basic information will enable one to determine tile size from the tile drainage chart on the next page.

The selected drainage coefficient must be applied to the correct area and grade of the tile line if the required capacity is to be provided. In places where no surface water is admitted directly to the tile line, the selected drainage coefficient should apply only to the land area that will be drained into the tile system. An exception is in places where runoff from an upland watershed spreads out over the area to be tile-drained, thus adding an additional load over that produced by actual rainfall. In that event, if the runoff cannot be diverted or channeled through the area to be drained, the drainage coefficient should be applied to the entire watershed area. When surface water is admitted to the tile line, the entire watershed served by the inlet should be used as the contributing area.

The smallest tile generally recommended is the 5-inch size. The recommendation is based on the need to provide good agricultural drainage for a long time and low cost of maintenance, and in view of construction methods and probable developments in crops and farming practices.

Four-inch tile is satisfactory only in mineral soils that contain only small amounts of fine silt and sand and on lines with grades of 0.1 percent or more.

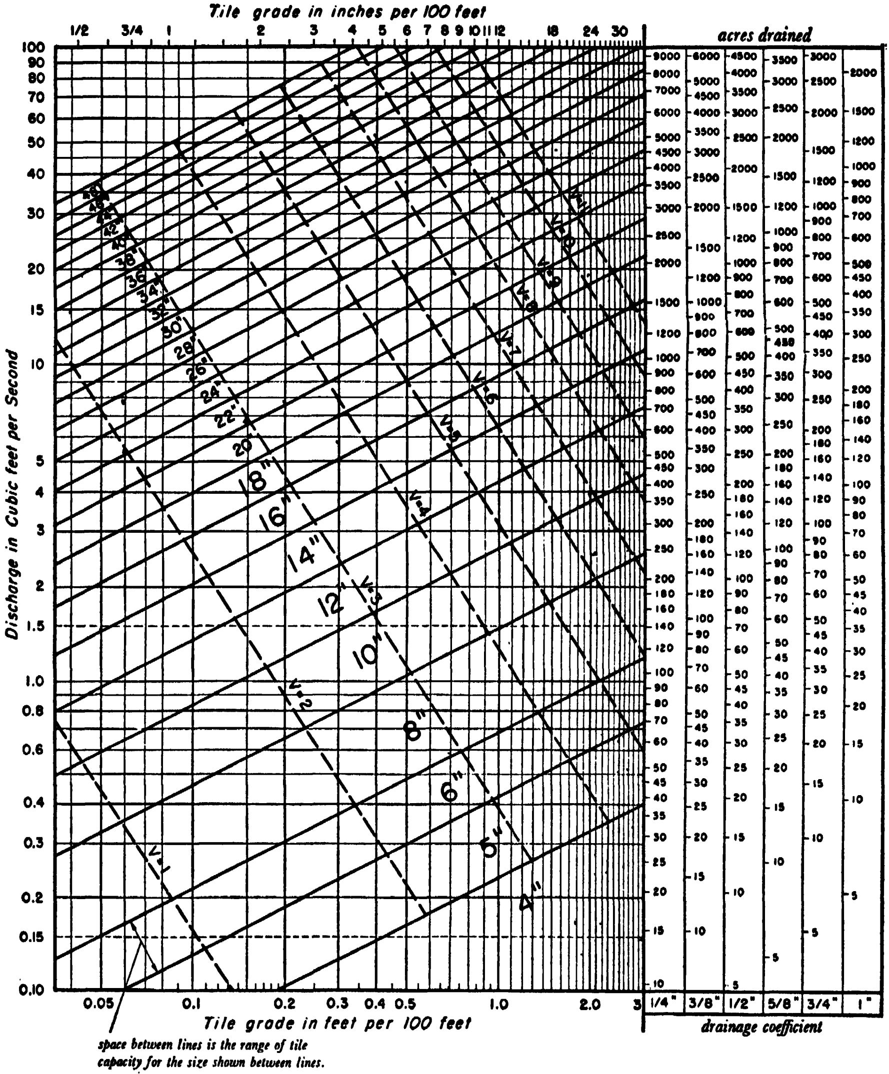
Six-inch tile, 18 and 24 inches long, should be the minimum for deep peat and muck soils because of shifting of tile alinements. Six-inch tile should also be used on lines with surface inlets.

When tile lines are to be used for intercepting seepage and springs, adequate field investigations must be made to determine the amount and extent of seepage. The watershed area, soils, stratifications, and local experience with similar systems should be considered in determining the size of tile to intercept hillside seepage. If it is impossible to determine the amount of flow from a spring or seep area, one should use 6-inch tile or larger.

The depth and spacing of tile also should be such as to lower the ground water between tile lines within 24 hours after a rain to a depth that cannot injure crops. The depth of the permanent water table after drainage is highly important, because that depth regulates the amount of soil where plant food is available to the plant roots. The depth and spacing of tile lines required to give the desired depth of permanent water table are influenced by tightness of the soil, amount and frequency of rainfall, seepage and surface water, and flatness of the land surface. Recommendations for depth and spacing according to soil types are available in some States. Most soil con-

Drain Tile Design Chart

Yarnell-Woodward Formula $v = 138r^{2/3}s^{1/2}$



How To Use Chart: (*1*) *Find the number of acres to be drained in the selected drainage coefficient column.* (*2*) *Project a horizontal line to the left until it intersects the vertical line representing the grade of the tile line shown at the bottom of the chart.* (*3*) *The tile size shown in the space between diagonal solid lines where the point of intersection occurs is the required size of tile to use.* (*4*) *The diagonal dotted lines show the velocity of flow in the tile.* (*5*) *Continue your horizontal line until it intersects the left vertical marginal line to find the discharge in cubic feet per second.*

servation districts have local guides that contain the information.

The average minimum depth for tile laterals in mineral soils should be at least 3 feet. Most experimental work shows increased crop yields for depths of 3.5 to 4 feet. The depth may be reduced to 2.5 feet, with laterals spaced

about 50 feet apart for slowly permeable soils, soils with extremely tight sand or rock layers that prohibit greater depth, and in fields where cropping conditions require rapid drainage of the upper horizon of the soil profile.

Organic soils should not be tiled until after initial subsidence has occurred. Such falling or lowering continues after the first stage and may be as much as 0.1 foot a year because of oxidation under cultivation, compaction, shrinkage, and wind erosion. The minimum depth of tile lateral in deep peat and muck therefore should never be less than 4 feet. Further information on the drainage of peat and muck soils is given in another chapter.

The very minimum of cover in mineral soils to protect the tile from breakage by heavy machinery should be 2 feet of soil over the tile. In organic soils the minimum should be 2.5 feet. When it is not feasible to have the minimum cover under waterways and road ditches, at the outlet end of the main or near structures, the tile should be replaced with metal pipe or other high-strength, continuous rigid pipe. The mains and submains should be deep enough to provide the specified depth for laterals and allow the laterals to be joined at the approximate center of the main tile.

The maximum depth at which tile can safely be laid varies with the width of the trench and depends on the crushing strength of the tile. Draintile should be so installed that the load on the tile does not exceed the required minimum average crushing strength, as set forth in *Tentative Specifications for Drain-tile*, publication C4–50T of the American Society for Testing Materials, 1916 Race Street, Philadelphia 3, Pa. The allowable maximum tile depths for various sizes of tile and width of trenches in thoroughly wet clay soil are given in the table of allowable draintile depths. The depths given in the

Allowable Draintile Depths

Tile size, in.	*ASTM class*	*Crushing strengths, lb. per lin. ft.*	*Width of trench in inches*								
			16	*18*	*20*	*22*	*24*	*26*	*28*	*30*	*36*
5	Standard	1,200	16.5	8.7	7.5	7.5	7.5	7.5	7.5	7.5	7.5
	Extra quality	1,600	Inf	Inf	12.2	9.5	9.5	9.5	9.5	9.5	9.5
6	Standard	1,200	Inf	8.8	6.8	6.6	6.6	6.6	6.6	6.6	6.6
	Extra quality	1,600	Inf	Inf	12.3	8.7	8.4	8.4	8.4	8.4	8.4
8	Standard	1,200	Inf	9.0	7.0	5.8	5.4	5.4	5.4	5.4	5.4
	Extra quality	1,600	Inf	Inf	12.5	8.8	7.3	6.9	6.9	6.9	6.9
10	Standard	1,200	Inf	9.2	7.2	6.0	5.3	4.9	4.9	4.9	4.9
	Extra quality	1,600	Inf	Inf	12.7	9.0	7.5	6.6	6.0	6.0	6.0
12	Standard	1,200	Inf	9.4	7.3	6.2	5.5	5.0	4.7	4.7	4.7
	Extra quality	1,600	Inf	Inf	12.9	9.2	7.7	6.8	6.1	5.6	5.6
15	Standard	1,300	....	...	8.6	7.1	6.3	5.8	5.2	4.9	4.7
	Extra quality	1,600	....	...	13.1	9.5	8.0	7.1	6.3	5.8	5.2
18	Standard	1,400	....	...	....	...	7.0	6.5	5.9	5.5	4.7
	Extra quality	1,800	....	...	....	...	9.6	8.5	7.5	6.9	5.7
21	Standard	1,550	....	...	....	...	...	...	6.7	6.2	5.0
	Extra quality	2,100	....	...	....	...	...	...	9.3	8.3	6.8
24	Standard	1,700	....	...	....	...	...	...	...	7.1	5.9
	Extra quality	2,400	....	...	....	...	...	...	...	10.0	7.9

NOTE 1.—Values given for the various trench widths are depths of trench in feet.

NOTE 2.—Crushing strengths given are averages in pounds per linear foot based on sand-bearing method, Specifications for Draintile, ASTM Designation C4-50T.

NOTE 3.—These values allow a safety factor of 1.5.

NOTE 4.—Width of trench is measured at top of tile.

NOTE 5.—Loadings were computed for wet clay soil at 120 lb. per cu. ft. Somewhat greater depths are permissible for lighter soils.

NOTE 6.—Ordinary pipe laying whereby the under side of the tile is well bedded on soil for 60 to 90 deg. of the circumference.

NOTE 7.—"Inf" indicates infinity.

Soil	*Permeability*	*Spacing in feet*
Clay and clay loam	Very slow	30– 70
Silt and silty clay loam	Slow to moderately slow	60–100
Sandy loam	Moderately slow to rapid	100–300
Mucks and peat		50–200

table are minimum and are safe only for less severe soil conditions.

The spacing between laterals should vary according to soil texture. When a system of parallel tile laterals is used for field crops, the spacing should be within the limits in the table on this page based on soil condition, crops, and local experience. For some special or high-value crops, spacings less than the minimum shown can be justified.

Both minimum and maximum grade limitations for drain tile govern what is considered good drainage practice.

Tile lines that are laid in most soils with little or no grade tend to fill up readily. Steep grades, which cause high velocities of flow, present a definite hazard to the mains, especially when they are flowing nearly full.

The minimum grade should be as great as possible on flat lands, considering the topography of the area. The grade of any tile line should not be flatter than 0.05 foot per 100 feet. The minimum grade in feet per 100 feet for 4-inch tile is 0.10 foot; for 5-inch tile, 0.07 foot; and for 6-inch tile, 0.05 foot.

The maximum grade for tile laterals often must vary with topographic conditions, and it is not always possible to adhere to a specific maximum grade. Single laterals are not likely to give difficulty because of steepness of grade under most soil conditions (except fine sandy soils), if the line is not overloaded. Furthermore, failure of a single lateral is not too serious, as it affects only one line. Tile sizes should be carefully determined for adequate capacity. If there is a change from a steep to a flatter grade, the size of the tile may need to be increased to provide adequate capacity. The maximum grades for laterals in fine sandy soils need more careful consideration, and special precautions are to be observed.

The maximum grade for tile mains varies with different soil materials and steepness of slope. Tile mains constructed with farm drain tile preferably should not be placed on grades of much more than 2 percent, but some locations and conditions may require the use of steep grades. The following special practices are recommended for tile lines laid on steep grades in different soil materials.

Great care is necessary in placing tile in sand and sandy loam soil on steep grades. Tile laid in sand on any appreciable grade is likely to cause trouble because free water, carrying loose sand particles, might enter the joints. Irregularities in the joints also cause disturbed flow in the tile. As velocity increases on steeper grades, turbulence becomes greater, and a hole may develop on the outside of the joint and cause shifting and blocking of the line. That can happen also in other soil materials but less readily than in sands.

It is good practice to use bell-type or tongue-and-groove-type sewer tile on grades of more than 1 percent if the tile line is designed for nearly full flow. On lines that will not run more than half full, draintile generally can be used on grades between 1 and 4 percent with good success if the tile is laid to a very tight fit, the joints are wrapped with a tar-impregnated paper or heavy burlap, and heavy soil is firmly tamped in place around the tile. Even on grades under 1 percent, such precautions are desirable to preserve the grade and alinement of the line.

The silt and silt loam soils are less hazardous for tile on steep grades than the sandy material. Regular draintile can be used on grades ranging from 0.5 to 2 percent by laying the tile to a tight fit and tamping heavy soil firmly around the tile. Sewer pipe should be used on grades of more than 2 percent when the main is designed for near-

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capacity flow. On lines designed to run not more than half full, draintile can be used on grades between 2 and 6 percent by laying the tile to a tight fit, wrapping the joints with a tar-impregnated paper, and tamping heavy soil firmly in place around the tile.

In clay loam and silty clay soils, only ordinary care in laying the draintile is required on grades of less than 1 percent. When regular draintile is used on grades between 1 and 6 percent, the tile should be laid to a tight fit, and heavy-textured soil tamped firmly around the pipe. On grades above 6 percent where the main is designed for near-capacity flow, sewer pipe provides the safest construction. If the main is designed to run not over half full, draintile can be used on grades from 6 to 15 percent by laying the tile to a tight fit, wrapping the joints with a tar-impregnated paper, and tamping heavy soil firmly in place around the tile.

If the tile mains are on steep grades, particularly those that are likely to flow nearly full, it is wise to protect the drain by installing a breather, or air vent, at the upper end of the steep section and a relief well at the point where the steep section changes to a flat section.

ALL TILE SYSTEMS require additional equipment if they are to work properly. Appurtenances and structures properly selected and used when needed will help prolong the life and increase the efficiency of the system.

Surface inlets generally are used in depressions or potholes where surface water collects in relatively large amounts and no natural outlet is available. If surface inlets are used, a larger tile main is needed than for only subsurface drainage. They add to the costs. Surface inlets should be used only when the construction of waterways for removing the impounded water is not feasible or is impractical.

Two accepted types of surface inlets are the blind inlet and the open inlet.

The blind inlet is most useful in open fields, as it does not obstruct farming operations. Its rate of removal of impounded water is much slower than that of the open inlet, and therefore it should be used in places where not much water is impounded. At least one inlet should be placed on each tile line passing through the depressed area. Another advantage is that small rubbish cannot enter the tile.

The blind inlet is made by filling a small section of the tile trench with broken tile, broken brick, stone, gravel, or crushed rock, or a combination of them. The fill around and about 6 inches above the tile should be carefully selected and placed. From that point up to within 12 to 18 inches of the ground surface, the material should be graded upward from coarse to fine, and should be covered with porous topsoil. For faster intake of the water and in places where silting is a problem, pea gravel, small stone, or coarse sand may be used in place of the porous topsoil. The blind inlet eventually will become sealed by silt and fail to operate. How long it will serve effectively depends on the placement of fill material and the amount of silt reaching the inlet. When the inlet fails to work properly, the filter material should be removed, cleaned, and replaced in the trench, or a new inlet constructed next to the old one.

The open inlet has a valuable advantage; it will permit a much greater volume of water per hour to enter the tile than will the blind inlet, so that the impounded water will be removed faster. But the tile main must be made larger to handle the increased flow and it must be protected against admission of rubbish and damage by field machinery.

It is good practice to locate the inlet on lateral lines or at least 20 feet to one side of the main. The top of the inlet should be covered with an iron grating, which will permit water to enter but prevent the entrance of grass, cornstalks, and other debris that might choke the tile drain. If the spacing of the grating bars is close enough to do

this job, the floating debris quite often collects on the grate and reduces or stops the flow of water into the drain. Constant inspection and removal of debris is therefore necessary. The possibility also exists that if sufficient head develops over the inlet, blowout in the main may be expected. The inlet should be located preferably in fence lines where it will not interfere with farming operations. If the inlet has to be located in an open field, it should either be protected by a fence or constructed with its top about 1 foot below the ground surface and then covered with small rocks; its location should be marked with a tall post. The rock covering will tend to reduce the rate of flow through the drain.

One type of surface inlet can be made of sewer pipe, whose joints are cemented. A sewer pipe T-branch is placed in the tile line at the location of the inlet. Vertical sewer pipe is connected to the spur of the T-branch. Two or three sections of sewer pipe, with cemented joints, should be placed in the line on each side of the T-branch. This type of inlet should be used only on lateral lines.

An offset type of inlet may be constructed of large sewer tile with cemented joints, concrete building blocks, cistern blocks, or any other light material. The inlet box is connected to the main by a short section of sewer pipe.

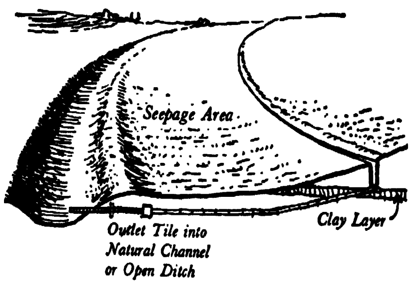
Surface water usually carries a large amount of sediment, which should be trapped before it has a chance to reach the tile main. That can be done by building a sediment trap into the surface inlet, or a sediment trap can be located immediately downstream from the inlet at some convenient location.

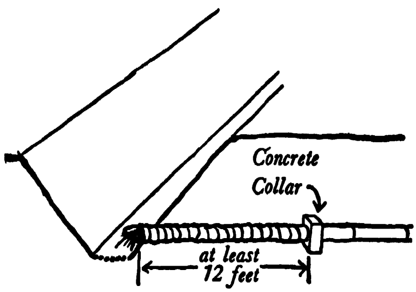
It is also wise to locate a relief well a short distance downgrade from the surface inlet. The relief well is less important if small inlets are attached to large lines; it is very important if large inlets discharge directly into any lines.

Relief wells relieve pressure in the line that might otherwise cause the tile line to blow out. A blowout will occur when the water pressure in the tile is greater than that in the soil, so that the water is forced out through the joints. A blowout washes soil from around the drain and permits the tile to get out of place.

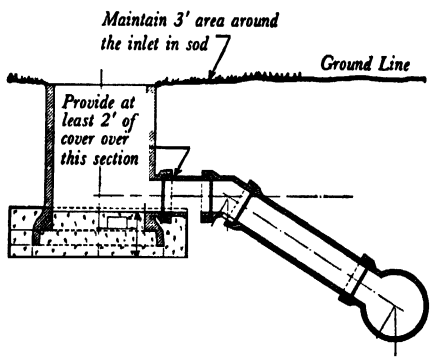
A relief well can be made by placing

Tile Drainage of Seepage Areas





When no surface water will enter the ditch at the location of the tile outlet, a section of continuous rigid pipe gives the best outlet protection.



Open surface inlet located off to one side of tile main. A larger sewer pipe T-branch is used for the riser.

a T-connection in the line and cementing sewer pipe vertically into the T. The pipe should extend about 1 foot above the ground unless provisions have been made in the design of the main for it to serve also as a surface inlet. The exposed end of the pipe should be covered with heavy wire mesh or some type of grating. The size of the riser should be equal to the diameter of the tile line or one or two sizes smaller, depending on the amount of overload.

Relief wells should be located at points where the tile line might become overloaded for a short time, such as at the end of a steep section and on lines that have surface inlets. They can also be used to advantage sometimes in improving the existing mains that are temporarily overloaded to the point of causing blowouts. In that case a good waterway must be available to carry away the discharge from the well. The installation of a relief line paralleling the existing main should be the first consideration, however.

Breathers, or air vents, to tile lines can remove trapped air. Thereby they improve flow and furnish a supply of fresh air, which will circulate through the system and ventilate the soil. The breathers also mark the location of the tile line and serve as inspection holes. They should be located at abrupt changes in grade and can be used to advantage on long mains, where they are placed approximately every quarter mile. The breather is made the same as the relief well, except that its vertical pipe need be only 4 inches in diameter.

The sediment trap is a manhole, or catch basin, in which a storage area is provided below the grade of the tile line for collecting the sediment that is carried into the trap. The trap is set so that the incoming tile discharges into a pool of water; the sediment sinks to the bottom of the trap, and clear water is carried away by the outgoing tile. Some type of baffle or 90° elbow, with bell facing downward in the well, should be attached to the outlet tile to promote desilting. Sediment traps should be used on tile lines that extend through fine sand pockets or large, sandy areas, where there is a tendency for fine sand to enter through the tile joint. They should also be used in connection with open surface inlets to desilt surface water admitted to the tile line.

The junction box is installed where two or more large tile lines join or where several lines join at different elevations. It is a rectangular or round well of concrete, some type of permanent blocks, such as concrete or cistern blocks, or bricks laid up in mortar. The size will vary according to number and diameter of lines that are to be joined at one location. A minimum size would be 2 feet by 2 feet.

The junction box preferably should be located in a protected place. The top of the box should extend about 1 foot above the ground to provide for easy inspection. The top should be covered with a cover of reinforced concrete or a metal manhole cover. If it is necessary to put the junction box in a cultivated field, the box should be constructed so that the top is at least 18 inches below the surface of the ground. The box should be fitted with a removable concrete cover, covered over with soil, and marked as to location. Besides joining lines, the junction box provides an ideal inspection manhole. If silt-removing devices are added, it can serve further as a silt trap. That additional use should be considered when the top of the manhole is above the ground.

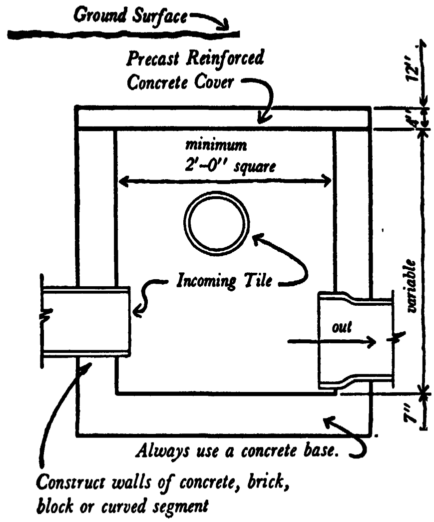
Protection of the tile outlet is necessary when the tile main outlets into an open ditch. The end of the tile should be protected against erosion and undermining. Two conditions are involved.

When no surface water will enter the ditch at the location of the tile outlet, a section of continuous rigid pipe should be used at the end of the tile line. At least two-thirds of its length (a minimum of 8 to 12 feet) should be imbedded into the ditch bank with the

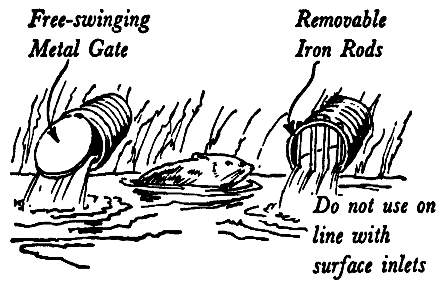
overhanging length discharging just beyond the toe of the ditch slope. A small concrete collar should be used to join the section of rigid pipe to the tile line. When the placement of a pipe projecting into the ditch will cause a serious ice jam or be damaged by floating ice or debris, the pipe should be recessed into the ditch bank and provisions made for the water to flow from the pipe out onto a paved section or apron of a small concrete or masonry structure.

When surface water must enter the ditch at the same location of the tile outlet, some type of structure should be used to outlet the tile and to lower safely the surface flow to the ditch. If there is no spoil bank, a straight-drop spillway is generally the best type. If there is a spoil bank and if sufficient temporary storage on the land is possible, a pipe drop inlet structure will usually provide the best and cheapest installation. Sometimes it may be possible to move the tile outlet out of the waterway or divert the surface water to another location, at least 60 to 75 feet away, and lower the surface flow into the ditch over a sod chute. If it is practical to do so, the tile outlet should be located upstream from the surface water outlet; it should then be protected by a pipe.

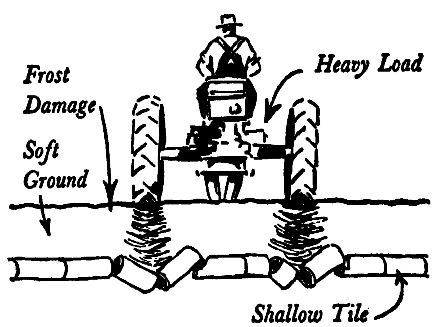
Swinging gates or a similar type of protection should be used on all tile outlets to exclude small animals unless the outlet is located so that it would be impossible for them to enter the tile at the outlet end. A simple swinging gate can easily be made of heavy galvanized sheet metal. The sheet metal should be large enough to extend well beyond the side of the outlet pipe except that the top part of the gate should be trimmed off to permit easy opening. Heavy wire attached to two holes in the top part of the pipe suspend the gate over the end of the pipe. The wire links supporting the gate should be large and loose for freedom of movement. Gratings or a catch screen should never be used on tile lines that have surface inlets because of the hazard of debris that



Plan for a submerged junction box.



Two methods for keeping small animals out of the tile line.



Shallow tile may be damaged by frost and heavy modern machinery.

might enter through the inlet and collect on the grating bars. Plant roots may be a problem with this type of grating.

A plan or location map of the location and size of all lines and the depth and grade of the main should be prepared for each installation. The map will be useful to the contractor during construction and, if corrected to reflect "as built" conditions, it will be of great value as a record of the installation. It is useful in locating lines for repairs and determining possibilities of additions and extensions to the system. The map also will be evidence of the added capital investment in drainage when the farm is sold. This record should be filed with the abstract or deed to the land.

SELECTING DRAINTILE that is strong and durable is important. The performance and life of a tile system will be affected greatly by the kind and quality of tile used. All tile installed should meet the requirements as set forth in *Specifications For Drainage Tile*.

Tile meeting those specifications will give lasting service under most conditions. Clay or concrete tile is satisfactory under normal conditions. Concrete tile that meets standard specifications of the American Society for Testing Materials resists frost. Clay draintile meeting ASTM specifications for extra quality is generally frost resistant. Soil acids and sulfates may affect concrete tile to a varying degree. Clay tile is not so affected. Concrete tile that meets the requirements for extra quality draintile in the ASTM specifications can generally be used in acid peat soils. If the soil or ground water contains acids or sulfates, however, the advice should be obtained from the local soil conservation district, county agricultural agent, or the State college of agriculture before tile is bought.

Tile that have deep cracks, large checks, lime spots, pebbled and honeycombed walls or that are out of round or warped should never be used. Tile should be straight, uniform, and circular, with smooth, square-cut edges so that it can be easily matched in the trench. A good tile must be dense, so that it will not absorb water and be easily damaged by freezing and thawing. The tile must be exceptionally strong if it is to stand up under the weight of heavy farm machinery. Proper curing of concrete tile after manufacture is essential before the tile is laid, so that it has sufficient strength to support the backfill and crossing of heavy machinery.

PROPER CONSTRUCTION of the tile line is the last essential for a good system. It is important to have a competent contractor, who should have good equipment and use targets or string lines in placing the tile on grades. Targets should always be used as a guide by which to finish the tile trench bottom to exact grade. Targets should be set at not less than three stakes along any given strip of continuous grade at one time. The grade stakes should be set 100 feet apart or less on straight lines and 50 feet or less on curves. Grade stakes should always be set with an engineer's level, because they are markers from the top of which all measurements are made.

Digging of the trench should start at the outlet and proceed upgrade. That permits any water that gets into the trench to flow away instead of collecting and causing damage to the sides and bottom. The trench should be dug so that the tile can be laid in straight lines and smooth curves, because that provides the least obstruction to flow and possible clogging. The trench width, measured at the top of the tile, should be about equal to the outside diameter of the tile plus about 0.5 feet. This clearance between tile and sides of trench is necessary for proper bedding and blinding of the tile. It is very important that the bottom of the trench be cut accurately to grade. Any trench that is cut below grade at any place should be filled back with graded gravel or well pulverized soil, which must be tamped enough to pro-

vide a firm foundation. Then the bottom of the trench must again be planed to grade and shape. The bottom of the trench should be rounded so that the tile will be imbedded in soil for 60° to 90° of its circumference. If a gradual curve is not possible or desired, a change in horizontal direction may be made in a junction box or manhole or by use of manufactured bends or fittings, so that the change in direction is a smooth curve.

Laying the tile also should begin at the lower end of the line and progress upgrade, following closely the excavation of the trench. The tile should be laid true to the line of the trench and firmly bedded in the bottom of the trench and on grade. If the tile does not fit properly against the one previously laid, it should be turned on its horizontal axis until it fits tightly at the top, and the open space is left at the bottom.

Joints or gaps between tile admit the drainage water into the line. It is important that the correct gap spacing be maintained, because tight joints in some soils will seal over and joints that are too large will permit soil to be washed into the tile. The gaps between tile must be varied according to soil conditions. Sandy soil requires a tight fit. The tile should be laid and turned to avoid excessive cracks at the joints. The gap should be about one-eighth inch for silt and loam soil. The minimum for clay soils is the same. But local experience sometimes indicates that a wider spacing should be used. Peat and muck soils require a spacing of one-fourth to three-eighths inch.

If large gaps occur between tiles, as on the outer side of a curve, the joints should be covered with broken pieces of tile or in some way just as good.

Junctions between laterals and main lines should be made by manufactured connections or branches for joining two tile lines. If connections are not available, the junction can be chipped, fitted, and sealed with cement mortar. Laterals should be connected into the main tile at the midpoint of the tile. On large tile lines it is well to lay a submain parallel to the main for collecting the lateral lines, thus eliminating the necessity of tapping the large main every 50 to 100 feet. The savings on large connections and the length of laterals will generally offset the cost of the submain.

Tree roots can enter the line through the gap between tiles and obstruct the flow of water. The roots may continue to grow until they have completely filled the line and stopped almost all the flow. That is most likely to happen if the line is fed by springs and carries water in the dry season. The roots enter the tile in search of moisture.

All water-loving trees, such as willow, elm, soft maple, and cottonwood should be removed, if possible, for a distance of about 100 feet on each side of the line. It is well to maintain a clearance of 50 feet from other trees. A closed drain should be constructed of sewer pipe with cemented joints if the trees cannot be removed or the line rerouted. This type of construction should extend through the root zone.

Construction in quicksand—water-bearing sand—requires extreme care to exclude sedimentary material from entering the tile and to secure uniform grades on firm foundations. If conditions permit, construction should be delayed until the soil profile is in its driest possible condition. Tile of exceptional quality and uniform in size, shape, and smoothness of ends should be selected and laid so as to insure the snuggest fit possible. Building paper saturated with coal tar should cover the upper two-thirds of the joint. When it is necessary only to extend the tile through a quicksand pocket, sewer pipe calked with okum or continuous rigid pipe may be used in place of draintile. If metal pipe is used, the joints should be wrapped with paper saturated with coal tar and clamped with manufactured connecting bands.

Well-constructed filters will generally serve to stabilize the subgrades. One successful method is to construct a gravel envelope by placing enough

graded gravel or crushed limestone in the trench to stabilize the subgrade. After the tile is laid, the saturated paper is placed over the upper two-thirds and is covered with graded stones. Another method is to excavate below grade to enough depth to encase the tile line with at least 4 inches of stable soil, either loam, clay, or a mixture of the two. Sometimes it is possible to stabilize the trench bottom by placing tough sod in the bottom of the trench and laying the tile on it. The tile should then be completely covered with sod before backfilling.

If quicksand conditions are bad, filters seldom furnish adequate support for the tile and the tile must be placed in a cradle. A cradle can be constructed by placing wooden planks in the bottom of the trench and nailing strips along the top edges to form a trough for the tile. The wooden planks should be approximately equal to the outside diameter of the tile. Junctions of the boards or strips are staggered in order to make the cradle rigid and thereby furnish support for the entire length. Occasionally the cradle has to be placed on piling so as to hold the grade.

Blinding consists of placing loose, mellow topsoil around and covering the tile to a depth of 6 to 12 inches. The covering lets water pass freely into the tile and holds the tile in place in case of rain before backfilling and during backfilling operations. Blinding should follow soon after the tile is laid. It is wise to blind all tile by the end of a day's work. Sand should not be placed directly on or around the tile. The soil should be carefully worked down around the tile so as not to disturb battered joints or the alinement of the tile. In sands or tight soils or where suitable topsoil is not available, a layer of several inches of well-graded gravel or coarse cinders spread over the tile prevents the joints from sealing and facilitates drainage. Vegetative material, such as marsh hay, straw, or corncobs, can be used for covering the joints, but the period of usefulness of these materials is limited.

Backfilling of the trench should be completed soon after the tile are blinded and should always be done before the backfill material freezes. All earth removed from the trench should be returned to and heaped above the ground at the trench in such a way as to insure against objectionable depressions once settlement has taken place. Backfilling is generally accomplished by tractor and plow, scraper, road grader, bulldozer, or motor patrol.

A WELL DESIGNED and constructed tile system will not require extensive maintenance, but the maintenance that is required is extremely important. One broken tile will stop up an entire line. Many tile systems and even parts of farms have been ruined because of neglect of the outlet.

The tile system should be inspected at least in the spring and fall each year and more often during the first year of operation. The outlet must be kept open and free of silt and debris at all times. The swinging gate on the outlet must be kept in good condition and working freely. If erosion is occurring at the outlet, immediate steps should be taken to correct the situation. Sediment traps should be inspected often and cleaned whenever necessary. It is good practice to walk the tile lines often and check for holes and washes. Repairs should be made promptly.

An adequately planned system, correctly installed and given suitable periodic maintenance, will insure good tile drainage for several generations.

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Outlet Ditches, Slopes, Banks, Dikes, and Levees

John G. Sutton

To have effective drainage systems, farmers need to give special attention to outlet ditches, side slopes and banks, and levees and dikes.

Outlet ditches must have ample capacity to dispose of runoff. They must be deep enough to drain low fields and to serve as outlets for tile drainage systems.

Usually the ditch system enters a stream or lake. How often they are flooded must be taken into account when ditches are made. Often it is necessary to survey a natural channel well below the point of outlet to determine whether the channel is big enough to handle the flow from the drainage system and whether the land along the channel will not be subjected to increased flooding hazards.

Natural topography fixes the general location of the ditches in most places. One problem then is to obtain long, straight tangents and regular curves to permit economical cultivation of the fields. It generally is not desirable to straighten outlet ditches if the excess cut exceeds 18 to 24 inches in depth or where the new location will encounter sand or unstable soils. The location of the ditches sometimes is fixed by farm boundaries.

Lateral ditches for large areas of prairie and river bottom lands generally have been spaced a mile apart. Thus, each quarter section of land has access to a ditch. If spacings are wider, or farms are smaller than 160 acres, a different arrangement of laterals is needed so each farm can have an adequate outlet. In some places public outlet ditches customarily do not touch every small farm. Groups of farmers then must join to construct a lateral ditch.

Standards have been worked out for the sizes of outlet ditches for different conditions. They are generally set up on curves, commonly known as drainage coefficients, which generally provide for different degrees of drainage to enable the engineer to plan ditches in accordance with topography and crop requirements.

A chart on the next page shows coefficients for the Midwestern States, where they have been of common use since 1938. Ditches built to the size indicated furnish agricultural drainage to the degree shown.

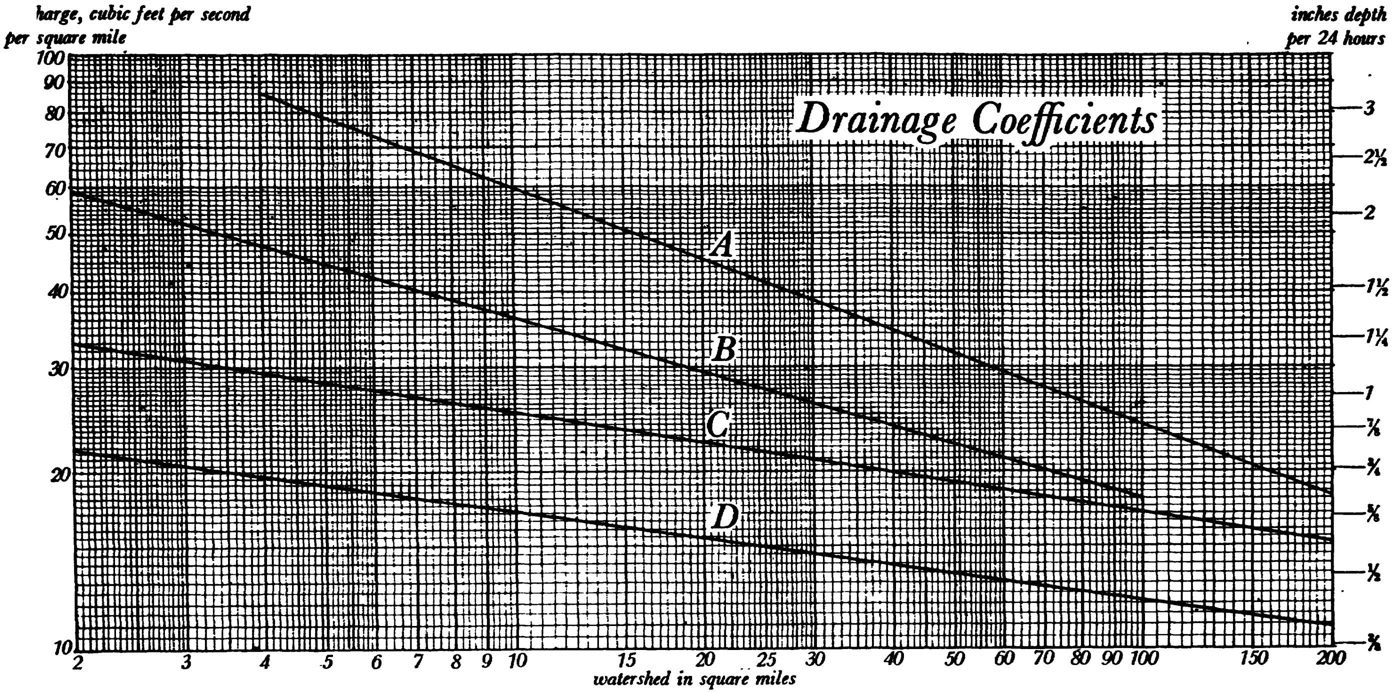
Curve A provides for a rate of runoff that will seldom be exceeded from flatlands and may be used for planning drainage channels for runoff from hilly land.

Curve B provides for excellent drainage and for a high degree of protection for farmsteads, truck crops, and agricultural areas where an excellent degree of drainage is needed. It may be used for runoff from rolling lands. Curve B provides about as high a degree of drainage as can be justified economically.

Curve C is most commonly used for planning agricultural systems where corn, small grain, and associated crops in rotations are the principal crops. Curve C provides good agricultural drainage for the average farm in the Midwest.

Curve D is used for drainage of low bottom lands of heavy soils that are to be used for hay or pasture and are not readily adapted for cultivated crops. Curve D is used in the locations where rainfall is less intense. For example, it is used in the glaciated areas of north central Iowa. During the 1954 flood, which caused damage in Des Moines and other places, Curve D provided a satisfactory degree of drainage for agricultural lands. Water collected in depressed areas and ponds and caused extensive crop damage, but the outlet ditches handled the drainage water as rapidly as it reached them.

The curves were developed by extensive streamflow studies by Civilian Conservation Corps drainage camps



A—For good protection from overflow (not maximum flood runoff). B—For excellent drainage. C—For very good agricultural drainage in Ohio, Indiana, Illinois, Iowa, and northern Missouri. For good agricultural drainage in Kentucky and southern Missouri. D—For fair agricultural drainage in Ohio, Indiana, Illinois, Iowa, and northern Missouri. Watershed area to be determined above each section of a ditch for which capacity is to be computed. Applicable only to flat watershed areas having average slope less than 25 feet per mile.

in Missouri, Illinois, Indiana, and Ohio in 1936–1938. Their use is limited to areas where the watershed does not slope more than 25 feet in a mile. Where the runoff from a considerable area will enter a drainage system, a ditch system is commonly designed on a higher curve. If the drainage outlet system is to be designed on a C curve and one of the laterals is to carry off runoff from steeper rolling lands, it would be proper to design that lateral according to the B curve. The increased size of the lateral would of course be taken into account by the engineer in planning the system downstream.

The curves have also been applied to the Northeastern States. Special curves have been developed, giving lower rates of runoff, for use in North Dakota and Minnesota. Similar curves, giving approximately 10 to 30 percent higher rates of runoff, have been developed and are used in the Southern States.

The chart also shows that the rate of runoff per square mile decreases as the watershed area increases. Thus, on the C curve, a discharge of 30 cubic feet per second per square mile is allowed for a watershed having 3.6 square miles. For a watershed area of 10.7 square miles, however, the drainage coefficient is reduced to 25 cubic feet per second per square mile. Use of the curve provides a balanced design throughout the drainage system, and makes possible the design of the most economical size ditches for watershed areas. Research is needed to fill in gaps in existing recommendations.

DETERMINATION of the side slopes and treatment of the spoil banks are among the most important points to be considered in planning effective open drains. They influence the stability of the ditch banks and ease maintenance. The width of the right-of-way should be sufficient for the ditch.

A 1.5:1 side slope is used for many outlet ditches—that is, 1.5 feet in horizontal distance to 1 foot in vertical distance. It is rather steep, but such a side slope will stand in most clay and clay loam soils. A side slope of 2:1 is ordinarily used for silt loams and medium-textured soils. Some soils are erosive, however, and will stand better on a steep slope. Ditchbanks often assume almost a vertical position. Therefore deep sands and loess soils are ordinarily dug with between 1:1 to 1.5:1 side slopes. Ditches dug in muck or peat soils often are built with 1.5:1 or steeper side slopes. It is wise to observe old drainage ditches in the locality in determining the stable side slopes.

Spoil banks should be spread so they are easy to farm. Preferably their side slopes should be not steeper than 6:1.

One of the main recent improvements in the design of outlet ditches is the handling of spoil banks. On spoil banks that spread, crops may be grown. Placing the spoil well away from the ditch reduces the earth pressures close to the ditch and makes it more stable and easier to maintain.

The distance from the top of the ditchbank to the edge of the spoil bank is called the berm. For stable soils, the berm should be at least twice the depth of the ditch. The minimum width should be 10 feet to permit easy maintenance with a dragline.

If a berm is covered with trees, it is usually permissible to cut the trees 12 to 18 inches above normal ground level and cover the stumps with excavated spoil material to provide a roadway. The practice is not desirable if the ditch is in unstable soil, because it increases the load on the ditch bank, nor should it be used if bank erosion will occur and allow stumps to fall in the channel. If maintenance work can be carried on from one bank, it may be wise to plan a passable roadway for a dragline along one berm and reduce the berm on the opposite bank to a minimum to save right-of-way. Berm widths are held to a minimum in irrigated areas to provide stability of ditchbanks, because spoil banks cannot be readily irrigated. Minimum berm widths and high spoil banks are speci-

fied also in the forest areas to save right-of-way and construction costs. A passable roadway along a ditch is highly important because it permits access by trucks and excavating equipment.

Ditchbanks may be unstable even if these recommendations are followed. Such conditions are frequently due to soil layers, such as quicksand, which have little resistance to sliding. Unstable soil layers are often encountered in ditchbanks where the chief material is a heavy soil that ordinarily will stand on a 1.5:1 slope. Such conditions are especially apt to be encountered in the initial construction of ditches where the subsoil is saturated. Without a specific remedy for this condition, it is generally best to plan on reexcavating the ditch after the slides have occurred and the ditchbanks have dried out and stabilized. Sometimes it is best to excavate the ditch to only part of its specified depth and finish the excavation after the soil near the ditch has drained. A good vegetative cover will help stabilize the ditch.

It is especially important to keep working on difficult slide areas until the required ditch section is obtained. A slide may act as a dam in a ditch and impair drainage of lands upstream.

THE VELOCITY of flow allowable in the drainage ditch varies with the soil type. In fine sand and sandy loam soils, the maximum nonerosive velocity in canals is 2.50 feet a second. Studies by Samuel Fortier and Fred C. Scobey showed that permissible velocity in firm loam is 3.5 feet a second; in fine gravel, 5 feet a second; and in stiff clay, 5 feet a second.

Erosive velocities occur at some places if the usual type of ditch is built. One solution may be to design the ditch wider and shallower so as to reduce the velocity. Or, the natural slope of the ground may be so great, the drop into the outlet channel so large, and soil conditions so unstable that grade-control structures are needed. Examples of what happened when those precautions were not followed can be seen along tributaries of the Missouri River in western Iowa and Missouri. Some of them have enlarged so much that the caving banks have seriously damaged the land.

Drainage ditches on flatlands may present a problem of too low a velocity. It is generally desirable there to plan the ditch as deep as practical in order to get the highest velocity and reduce silting.

Depths of the outlet ditches differ according to whether they are for surface, tile, or irrigated land drainage. For surface drainage they need be only deep enough to handle the runoff they receive. Outlet ditch grade for tile drainage systems, however, should be at least 18 inches below the bottom grade of the tile outlet. Thereby some sediment can be deposited in the outlet ditch before the tile drainage system is affected. If tile drains are planned, the outlet ditches in the humid area should be not less than 5 feet deep.

Ditches may be quite deep in stable soils, as better hydraulic efficiency is obtained with a deeper ditch. In sandy soils in the humid area ditches are made often wide and shallow for stability. The depth of the ditch should increase uniformly downstream. Care should be taken to obtain a uniform bottom grade and avoid humps in the gradeline.

Much deeper ditches are required in the irrigated areas where a ditch has to cut into gravel or sand and intercept ground water. Many ditches must be 10 or 12 feet deep or even deeper to reach the permeable layer. The ground water should not be allowed to rise above a 5-foot depth, to prevent the rise of alkali and saline salts. The depth should be at least 6.5 to 8 feet for tile drains and 8 to 10 feet for open ditches into which tile drains empty.

The most common type of drainage ditch structure is a culvert or bridge. Difficulty has been encountered where highway, road, or railroad culverts were placed too high or were too small. Their replacement often has

been difficult and costly. Culverts and bridges should be carefully planned to meet the future drainage requirements so as to avoid unnecessary expense later.

The Ohio Turnpike exemplifies planning for future requirements. It crosses 13 counties in northwestern Ohio, nearly all of which is flat, drained land. The width of right-of-way was generally 250 to 600 feet. The highway crossed many tile systems, with laterals spaced not more than 60 feet apart, and many open ditches. Engineers at the outset planned for adequate bridges and culverts to take care of existing drainage systems and provide for future installations. The consulting engineer employed a Department of Agriculture engineer, whose assignment was to work on drainage to help solve the complex and difficult problems encountered in this construction. The plans for the alteration and reconstruction of existing agricultural systems, the design of turnpike drainage structures, provisions for future agricultural drainage, and improvement of existing drainage systems were described by Henry N. Luebcke, in an article in the magazine Roads and Streets for July 1953.

The engineers worked out plans for the installation of collector mains in places that needed drainage but had no other outlets. Some of the mains are below existing tile systems, or may be sealed at both ends, so as to provide for future drainage needs. Special attention was given to providing bridges and culverts large enough to accommodate proper drainage flow and to minimum depths of culverts and bridges to serve existing and future drainage systems.

The poor maintenance of drainage enterprises probably entered into the planning of some highway culverts—some had been placed at adequate depths, but debris and sediment in neglected drains had partly blocked the culverts. Therefore, when new highways are laid out, the tendency for highway engineers is to place culverts as high as possible in relation to the bottom grade of the existing drainage ditches.

Highway departments often place culverts or bridges in order to meet existing depths of drains, but when farmers decide to rehabilitate their drainage systems they discover that the culverts or the bridges then are too high. Expensive reconstruction of the highway structures may be required to meet the drainage needs. Culverts and bridges therefore should be built to meet future needs, not necessarily the current requirements.

Great progress has been made in the installation of pipe and drop structures where laterals and field drains enter outlet ditches with an abrupt drop in grade. Mostly pipe drops of various materials are used. In many places pipes may be seen projecting into the outlet ditch.

Sod flumes are used sometimes to control erosion. They should discharge into a recessed area 10 to 15 feet back from the bottom of the outlet ditch. The purpose of the recessed area is to accumulate sediment until vegetation becomes well established. The chute should rise on a grade not steeper than 8:1 to intersect the grade of lateral or field drain.

Natural vegetation in some places will soon develop a good cover after the inlet and chute are excavated to proper dimension, but sometimes it has to be established. Sod may be wired down or may be placed in bags to hold it in place until it becomes firmly rooted.

Swinging watergates are recommended for outlet ditches where a fence crossing is required. Ordinary fences across drainage ditches collect debris, cause excessive siltation, and are difficult to control. If a fence is needed across a drainage ditch, it is better to use a swinging watergate that will open up when the water rises. A well-designed structure will permit floating debris to pass underneath.

Such gates are needed if the ditch is to be pastured. Because pasturing is

such an effective maintenance measure, it is usually to the advantage of a drainage enterprise to spend the extra funds necessary to install watergates.

Drainage ditches occasionally have a steep grade, and some fall must be taken up by a drop structure to avoid erosion. Bank-protection measures such as riprap and piling, are used sometimes to control erosion in curves and bends.

LEVEES AND DIKES may be necessary. Many of the smaller ones are built and maintained by drainage enterprises. Large levees along major rivers, built by the Corps of Engineers, protect bottom lands from overflow and have made possible the drainage of large acreages along the Mississippi, Ohio, Missouri, Illinois, Red, and San Joaquin Rivers. Dikes and levees built by drainage enterprises and farmers are usually along the smaller streams. They have some disadvantages: The flood height along the stream channel, the rate at which the flood crest moves downstream, the maximum discharge for some distance downstream, and the stream velocity and tendency for erosion to occur are all increased when floodwaters are confined between levees. Flood storage is reduced.

One should be especially cautious about building levees along small streams that have steep watershed areas and are subject to rapid rises to flood stage. Often flood storage reservoirs and watershed protection and improvement measures need to be combined to provide an effective drainage system for the bottom lands.

Among the best locations for small levees and dikes are wide stream bottoms, where a large area of agricultural land is thereby protected and the benefits are large in relation to the cost. Another is on land near lakes or large rivers that is subject to overflow or backwater and flood heights are well known.

Study of maximum flood heights and frequencies should precede levee construction. Agricultural levees usually should be built 2 or 3 feet higher than the flood stage for which it is designed. The height of the levee above the design flood is called freeboard.

It is impractical to design levees to provide protection against all major floods. For example, the flood of the Ohio River in January 1937 overtopped many local levees and dikes by several feet. It exceeded all previous floods. A study of levees and dikes in the flood areas indicated that most drainage enterprises and farmers could not afford to protect their land against such a flood, but they could afford to build dikes and levees that would protect the land against a flood occurring once in 10 or 25 years.

Before small dikes and levees are built, all should know how much protection they will provide. Farmers should plan to use their lands for special crop rotations if the dikes are likely to be overtopped every few years.

Construction features of agricultural levees depend on the location and soils. The top width usually should be not less than 8 feet, so a truck can be used along a levee for inspection, maintenance work, and flood repairs. If it is not practical to use the top of the levee for a roadway, the crown width may be 4 feet for dikes under 6 feet wide and 6 feet for dikes 6 to 12 feet wide.

Side slopes should be made 3:1 on small dikes so a pasture can be established and weeds mowed. Crawler tractors can be operated on 3:1 side slopes, although gentler slopes are desirable.

If it is not feasible to build the dikes with flat side slopes, the slopes may be steeper, as determined by the stability of the soil and other construction requirements. Always, though, methods of maintenance should be carefully planned for.

The area on which the levee will rest should be cleared of brush and trees, the stumps and roots grubbed out, and the topsoil removed before construction is begun. The foundation area should be plowed to provide a good bond between it and the levee. A muck

ditch may be desirable if sand layers or other weak planes exist. The muck ditch usually should be 4 to 6 feet deep and 3 to 6 feet wide and be filled with a nearly impermeable soil. It is desirable to build the levee by placing and compacting thin layers of soil. Another desirable practice is to spread topsoil over the surface of the levee to encourage a good stand of grass. It is desirable in humid areas to maintain levees and dikes by pasturing them. A good sod prevents erosion, and cattle trampling over a levee will lessen the danger from rodents.

When water is high work crews should be ready to use sandbags and other methods to protect the dikes and levees.

THE MOST COMMON PROBLEM in maintaining drainage systems is keeping undesirable vegetation under control in open ditches. Otherwise a drainage system soon loses some of its effectiveness. A ditch 15 feet wide and 4 feet deep in Louisiana had a measured capacity just one-tenth of its original designed capacity only 2 years after it was excavated. The damage was caused by a heavy growth of grasses and indigo. That is an extreme example, but uncontrolled brush and trees can reduce the capacity of a ditch one-third to one-half of its proper carrying capacity in 3 to 5 years. Fences and other obstructions also reduce the carrying capacity of ditches.

Regular maintenance operations should be carried out to control the vegetation. Considerable handwork is required to cut the brush and small trees, remove obstructions, and repair gates. Hand labor is so expensive that other methods are chosen wherever possible.

It is generally desirable and feasible in the humid area to obtain a close-growing cover of grasses to stabilize the ditchbank and berm. A good grass cover will reduce the growth of brush and trees and reduce the amount of handwork, because once established, it may be maintained by mowing, pasturing, chemicals, or a combination of practices.

Mowing to maintain spoil banks, berms, and ditches is economical and effective if the side slopes are not too steep. For safety, side slopes on which farm tractors are to be operated should be made 4:1 or flatter. Surface drains are usually built with very gentle side slopes, and mowing is a common method of maintenance.

Gentle side slopes require too much excavation and right-of-way for general use on deep outlet ditches. Part of the bank may be mowed, however, by using a mower that drops the blade at an angle of 45 degrees. Effective work can be done with such mowers from the berm and from the bottom of the ditch when it is dry.

Grazing by livestock has kept some drainage ditches in good condition for as long as 20 years. The grazing prevented the growth of undesirable vegetation. But stock should not be allowed to overgraze ditches. They should not be allowed on the banks when they are saturated or during freezing and thawing weather. Temporary electric fences may be used to control grazing. Hogs should be kept out of deep ditches, because they root out the vegetation and cause excessive ditchbank erosion. Often it is desirable to dig a water hole near a ditch for hogs, but to fence them out of the drainage ditch.

Ramps at intervals permit cattle to get in and out of a ditch without climbing the banks. The ramps may be on a 3:1 or 4:1 slope and may be 6 to 10 feet wide.

BURNING in winter or early spring, when the vegetation is dry but the ground is wet, can result in satisfactory control of undesirable vegetation in drainage ditches. A light wind helps carry a quick-burning fire through the brush and tall weeds. If the ditch is burned over when the ground is frozen, there is little likelihood of the fire getting out of control. Burning is even more effective if the brush is cut and piled.

Some drainage enterprises and landowners have used oil burners to control vegetation by regular burning during the growing season. Usually the first burn will kill the green vegetation and stunt the growth. A second burning about 2 weeks later will get rid of the dry material left after the first burning. Fire must be used carefully, especially when crops and structures are nearby.

CHEMICALS, such as 2,4-D and 2,4,5-T, are widely used to control unwanted vegetation. Farmers who have not used them will do well to test them before undertaking extensive operations so as to estimate costs and the amounts required for effective control. Care should be taken in applying them lest the chemicals damage adjoining crops. Broadleaf crops and some truck crops are particularly susceptible to damage. Esters of 2,4-D can drift a half mile or more and kill cotton. Chemical companies have prepared informative bulletins about using their products.

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The Use of Pumps for Drainage

John G. Sutton

The use of pumps for drainage has made possible many large drainage projects, one of which is the Zuider Zee project, undertaken by the Government of the Netherlands.

For centuries the Dutch have been reclaiming lands from the sea and draining lakes by constructing dikes, pumping plants, and drainage systems. The new lands have added greatly to the agricultural production and general prosperity of the Netherlands.

Their first efforts to reclaim land began shortly after A. D. 1200. About 80,000 acres were reclaimed before A. D. 1300. Reclamation has continued steadily since then, despite setbacks when storms broke the dikes and caused great loss of life and property and when dikes were breached in war, causing flows that destroyed buildings and structures, filled ditches with sediment, and let ruinous salt water cover the land. The Dutch made repairs each time. They always rebuild their dikes.

In the 750 years that the Dutch have been at this work, they have reclaimed about 1,453,000 acres, of which the Zuider Zee project has contributed 168,000 acres.

The first projects depended on tide gates and gravity drainage. An important advance was the introduction about 400 years ago of windmills for pump drainage; in the 16th and 17th centuries they drained several hundred thousand acres. Some of the lands are more than 12 feet below sea level. During the past century the picturesque windmills have been replaced largely by steam and internal-combustion engines and electric motors, which drive the pumps.

THE UNITED STATES surpasses the Netherlands in area drained by pumps.

Many American projects embrace 3,000 to 20,000 acres. River bottoms, lake and coastal plains, peat land, and irrigated lands are the main types of land reclaimed by pump drainage. Interest in small pumping plants for draining individual farms has grown because of the increase in available electricity, tractors, and internal-combustion engines to drive pumps.

Drainage pumping plants that serve large acreages in the United States are located principally in Illinois, Iowa, Missouri, Louisiana, Florida, and California. In the 1950 census, 378 drainage enterprises reported the use of pumps, which served 1,696,586 acres. That does not include pumping plants in States listed as county-drain States, nor does it include data from irrigation enterprises that had installed their own drainage pumping plants.

The area served by pumps in 1950 in California was 694,023 acres; in Illinois, 315,363 acres; Florida, 293,124; Louisiana, 179,266; Missouri, 67,217. In Iowa, a county-drain State, 81,754 acres were served by pumps in 1940. Drainage pumping plants, which drain smaller acreages, have been installed by drainage enterprises in Indiana, Michigan, Wisconsin, Minnesota, Nebraska, Georgia, Arkansas, Texas, Arizona, Idaho, Oregon, and Washington.

The projects have reclaimed swamp and overflow land which otherwise would be of little value for farming. The fertility of the drained soil has justified the cost. Many of the lands are among the most fertile in the country. They are mostly flat and low and therefore are easy to irrigate.

EXAMPLES OF BENEFITS from pump drainage are typified by the drainage pumping districts in the upper Mississippi Valley. The higher land in the bottoms was farmed in the early days, but the farmers often lost crops because of flooding by the river. The landowners in 1900 or so began the intensive development of the area by building levees and pumping plants.

Many of the early attempts at drainage meant only failures. The breaching of levees during floods destroyed crops and damaged roads and buildings. When levees break, a lake several miles long may be formed. High and constant wave wash, because of the long distances over which the wind sweeps, often ruins a levee. Each time the levees broke they were built higher. The Federal and State Governments provided financial help for reconstructing the dikes after the bad flood of 1927.

Costly mistakes were made in installing the early pumping plants. Often too little attention was paid to getting efficient equipment. The pumps were not adapted to the head against which they would be required to operate. Sometimes no provisions were made for varying the speed of the pumps in accordance with lift requirements. Because many of the discharge pipes were not submerged, it was necessary to pump against the maximum lift to the top of the levee. Little attention was given to designing pumps along sound hydraulic principles. Plants frequently were neglected. Equipment was ruined by lack of oiling and repair work. Many operators failed to adjust the speed of pumps, even when they could. Many pumps were operated at capacity so the operator could finish his work quickly, regardless of wear on equipment or cost of operation.

After costly experience, principles of efficient design and operation were developed.

Many of the drainage districts were just getting well underway when the agricultural depressions of the 1920's and 1930's occurred. Drainage taxes were high, and many could not meet payments on their bonded indebtedness. Many were refinanced by the Reconstruction Finance Corporation, the bondholders accepting reduced payments.

Very likely the bondholders and original landowners would have come out all right financially had they been able to hold on to their investments during the depression. Much of the land is now valued at several hundred

dollars an acre. It can produce up to 125 bushels of corn an acre.

The total drainage costs in the upper Mississippi Valley, including levees, drains, and pumping plants, originally averaged 40 to 100 dollars an acre. Prewar cost of pumping was 1 to 3 dollars an acre, including interest, depreciation, and operating expenses. Costs in 1955 would be double that, or more.

In planning effective pump drainage, it is highly important to select pumps, motors, or engines and construct the pumping plant so that it will have adequate capacity at the maximum lift. Crop losses may be large during periods of heavy rainfall if the pumping plant is too small. Many of the original pumping plants were too small.

Descriptions of present equipment in use in drainage enterprises and recommendations for required capacity are given in the following paragraphs for the principal pumping locations. Many drainage pumps are required in other areas, but pumping capacities may be determined by comparison with one of the areas described.

THE BOTTOM LANDS along the upper Mississippi and Illinois Rivers include 450,000 acres served by drainage pumps in Illinois, Iowa, and Missouri. The lands lie along the Illinois River south of Hennepin, Ill., and along the upper Mississippi River between Savanna, Ill., and St. Louis, Mo.

About 70 pumping districts, which range from 1,500 to 20,000 acres, are in the area. Most of them extend 5 to 10 miles along the river and cover the bottom lands, which are ordinarily 2 to 4 miles wide from the bank of the river to the bluffs. Levees were built to protect the districts from overflow from the rivers. Diversion channels divert hill water from the bottom land. Open ditches and tile collect the drainage water and conduct it to the lower ends of the districts. There the pumping plants lift the water over the levees into the rivers. Many of the drainage districts used to have gravity drainage through sluiceways. The building of dams for navigation, however, has largely ended the use of sluiceways, and the runoff water must be pumped.

The 1950 census of drainage listed 47 enterprises in Illinois. Their pumping plants had a rated plant capacity of 21,020 horsepower and served 315,363 acres. The pumps had an average rated capacity of 10.6 gallons a minute per acre.

The power for 23 drainage enterprises was supplied by 9,800 horsepower of internal-combustion engines. Diesel-type engines comprised most of the power units. Power for 16 enterprises was supplied by electric motors with a total rated capacity of 5,122 horsepower. There were 76 centrifugal pumps with an average capacity of 28,200 gallons a minute each. They were used so widely because of the high lift—15 to 25 feet—against which the pumps operate. Eleven mixed-flow pumps had an average capacity of 40,000 gallons a minute. Ten axial-flow, or propeller, pumps had an average capacity of 18,100 gallons.

In 17 plants in the upper Mississippi Valley in Illinois, Iowa, and Missouri, large pumping plants provided adequate drainage when the capacity ranged from 0.33 to 0.55 inch in depth from the watershed in 24 hours. That equals an approximate range of 6 to 10 gallons a minute per acre of drainage capacity. One inch of runoff for 24 hours is equivalent of 18.86 gallons a minute per acre. The capacities were adequate for drainage pumping from tracts of about 3,000 to 20,000 acres. The districts were along the Illinois River below Peoria and along the upper Mississippi Valley between Alton, Ill., and Burlington, Iowa. Variations in capacity in those areas were related to the amount of seepage. A formula for determining the runoff was developed.

For areas smaller than 3,000 acres in the upper Mississippi Valley, the required pump capacities are determined by estimating the required capacity of

open ditches to obtain adequate drainage, adding the estimated seepage, and deducting storage.

The pumping enterprises of Louisiana are located in the Mississippi delta and coastal areas. Dikes and the pumping lifts are lower than in the upper Mississippi Valley. The land served by pumps in Louisiana increased 46 percent between 1940 and 1950. Thirty drainage pumping enterprises in Louisiana in 1950 had 15,041-horsepower rated capacity and 4,282,000 gallons a minute pump capacity. The plants served 179,266 acres—equivalent to 23.9 gallons a minute per acre, or a depth of 1.27 inches in 24 hours from the land drained. Design standards of the Department of Agriculture provide for a higher plant capacity. There were 37 centrifugal, 32 axial-flow, 1 mixed-flow, and 32 unclassified pumps. Because the lifts are lower, axial-flow pumps are used more extensively than in the upper Mississippi Valley. Power to operate the pumps was supplied chiefly by internal-combustion engines, but some electric and steam power units were in use.

The required plant capacities for Louisiana and Texas are considerably higher than required in the upper Mississippi Valley.

A run-off capacity of 3 inches in 24 hours, including pumping capacity and the storage capacity, is recommended along the gulf coast—on flat tracts smaller than 3,000 acres. Storage is computed as storage available in areas below the elevation of the lowest cultivated land and normal water level. The small ditch storage can be disregarded. If a reservoir storage in a pumping district is 1 inch per 24 hours, the pumping plant should be designed for not less than 2 inches per 24 hours. The combined capacity figure of 3 inches per 24 hours applies to land used mainly for growing sugarcane. A greater capacity is usually advisable for special or truck crops or if property requires better protection. The recommended combined pumping and reservoir capacities may be 2 inches per 24 hours if the main crop is rice or pasture. These rates apply to the area along the gulf coast of Louisiana and Texas south of a line from Natchez, Miss., to Natchitoches, La., then roughly parallel to the gulf coast to Victoria, Tex.

North of that line and in Arkansas, the total pumping capacity and storage capacities may be reduced by 20 percent to 2.4 inches per 24 hours for land used principally for cotton and to 1.6 inches per 24 hours for rice or pastureland.

Many of the successful districts started out with smaller capacity but have increased them.

In Florida, most of the land served by pumps is in the Lake Okeechobee-Everglades area of southern Florida, which is nearly all peat lands. The average fall of the large outlet canals is approximately 0.2 foot a mile. About 60 percent of the annual rainfall of 55 inches occurs from June through September, when farming activities are slow and pumping can be greatly reduced on truck lands.

Many of the pumps can pump to or from the land served, and thus keep the water tables at a fairly uniform depth. The term "water control" is commonly used to include either raising or lowering the water table as conditions may require. Most pumping, however, is required for drainage. Pumping onto the land usually is done in February or March when the rainfall is light and spring crops are planted.

Nearly all the pumps are of the axial-flow or propeller type. Some are large screw pumps; the smaller propeller pumps commonly pump 10,000 to 30,000 gallons a minute. The maximum pumping lifts are 5 to 9 feet; the average lifts are 4 to 5 feet. Very little or no pumping is needed for drainage when the rainfall is light and Lake Okeechobee is at a low level.

The land served by pumps in Florida increased from 185,693 acres in 1940

to 293,124 acres in 1950. The reported pump capacities average 28.6 gallons a minute per acre, or a depth of 1.53 inches in 24 hours. The average pump capacity in 1940 was 18.2 gallons a minute per acre, or a depth of 0.96 inch in 24 hours.

The 99 enterprises in Florida in 1950 had 28,129-horsepower engine capacity. Nearly all the pumping enterprises were driven by diesel-type engines. Of the 354 pumps listed in 1950, there are 341 axial-flow or propeller pumps and 5 mixed-flow pumps.

For open-ditch drainage of the Florida Everglades the engineering board of review developed and recommended the following formula:

$$Q=\frac{69.1}{M}+9.6$$

in which Q is runoff in cubic feet a second per square mile of drainage area, and M is drainage area in square miles.

This formula has been used by L. A. Jones, of the Department of Agriculture, in preparing plans for water control of organic soils of the region. The formula provides 1-inch runoff depth per 24 hours from 16 square miles, 0.75 inch from 43 square miles, and 0.5 inch from 322 square miles. The formula assumes that the land will be overflowed for short periods after heavy rainfall. It is not intended to provide complete protection from flooding.

Many of the northern Everglades pumping districts serve 5 to 13 sections of land, on much of which sugarcane is grown. Most of the pumping plants were designed to remove 1-inch runoff per 24 hours. The 1-inch rate is generally ample for growing sugarcane on the organic soils of the area—even for areas smaller than the formula indicates.

Truck crops have suffered losses, however, when the capacity was only 1 inch per 24 hours. The following rates are recommended by B. S. Clayton, of the Department of Agriculture, for land used for truck crops in organic soils: 3.0 inches for 1 section of land or less, 2.0 inches for 2 to 3 sections of land, 1.4 inches for 4 to 9 sections, and 1.0 inch for 10 to 16 sections. Those rates are approximately those given by the runoff formula quoted earlier. A long pumping record at the Everglades experiment station at Belle Glade, Fla., indicated that a runoff of 3 inches per 24 hours was needed to protect crops on areas of 1 square mile or less.

Many pumping plants have been installed to serve pastureland. The plants usually drain 2 to 4 sections of land. A runoff of 1 to 2 inches, commonly provided for these grazing areas, has seemed adequate.

In California, low-lift drainage pumps drain river bottoms, and high-lift pumps in drainage wells drain irrigated land. Typical of low-lift drainage pumping is the reclamation of delta lands along the San Joaquin River, where large acreages of organic and mineral soil have been reclaimed by diking and pumping.

Pumping lifts vary considerably with the maximum lift, often 10 to 20 feet. In many of the pumping districts, water is admitted through pipes in the levees for irrigation. Seepage and excess irrigation water affect the amounts of water that must be pumped. In 1940 in California, 135 drainage and irrigation enterprises operated drainage pumps, which served 1,220,062 acres and had a total capacity of 5,727,787 gallons a minute. Nearly all were operated by electric power.

Low-lift pumping is done chiefly by means of propeller and centrifugal pumps. The 68 propeller-type pumps served 122,947 acres and had an average capacity of 5.5 gallons a minute per acre. The 168 centrifugal pumps served 456,688 acres and had an average capacity of 6.7 gallons a minute.

California also had many deep-well drainage pumps for irrigated land. These are classified as turbine pumps; 334 such pumps served 377,760 acres in 1940. The average capacity reported was 1.1 gallons a minute per acre.

Many deep-well turbine pumps have a low capacity per acre, but the aver-

age capacity reported was unusually low. Many drainage wells pump 2 to 4 gallons a minute per acre.

Investigations are needed to determine the feasibility of draining irrigated lands by pumping. Usually it is cheaper to drain by ditches or tile if permeable layers of soil are within 8 to 12 feet of the surface.

Pump drainage of irrigated lands may be feasible if water-bearing gravel or sand layers are encountered at depths from 20 to 100 feet and surface drains are not effective. Pumping tests usually are needed to determine the yield of water and the drawdown from wells. If results are favorable, pump designs are based on results from the test well. Most deep-well turbine pumps used for drainage have a capacity of 300 to 1,500 gallons a minute and serve 100 to 640 acres.

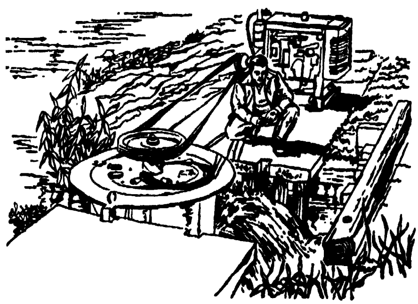
If water is used for irrigation, much of the cost of pumping may be allocated to irrigation. Irrigation enterprises often install dual-purpose pumps to lower a high water table and obtain additional water for irrigation.

Good operating efficiency of plants is obtained by selecting pumps based on the amount of pumping to be done. If a plant operates a large part of the time, it is well to choose more efficient pumps at added initial cost. If a high capacity is required but the total annual amounts of pumping will be small, it may be more economical to obtain less expensive pumps with high capacity but lower operating efficiency. Small farm pumping units that operate only a small part of the time may be quite simple.

Types of pumps used for drainage include propeller or axial-flow, mixed-flow pumps, centrifugal pumps, and turbine pumps.

The axial-flow, screw, or propeller pump, is especially adapted for low-head drainage pumping. The impeller has several blades, like those of a ship propeller. Blades are set on the shaft at angles determined according to the head and speed. The direction of flow through the pump does not change, as in a centrifugal pump. A spiral motion of the water results from the screw action but may be corrected by diffusion vanes. The type has been used extensively where the maximum static lift is less than 10 feet. One disadvantage is that the discharge falls rapidly at heads above that for which the pump is designed. The horsepower required tends to rise at higher heads, so adequate power must be provided to drive the pump at the maximum lift. The maximum static lift and the maximum total head against which this type of pump will operate should be determined accurately.

This type of pump can be built so the flow can be reversed if pumping is



needed for both irrigation and drainage—an advantage, especially if control of the water table is important.

A cheap propeller-type pump has been made with a propeller like a boat propeller inside a casing, a straight piece of welded steel pipe. Many have been installed by farmers for draining tracts smaller than 200 acres. Little is known about the efficiency of such pumps. A few have been built with such light outside casings that blocks of wood passing the screen have broken through the casing.

The mixed-flow pump has an open vane, curved-blade impeller, which combines the screw and centrifugal principles in building up the pressure head. It operates efficiently against higher heads than the propeller pump. With one change in speed, a typical

mixed-flow pump operated in tests at 70 to 80 percent efficiency at all heads from 6.5 to 26 feet. The discharge did not go down very much at the higher heads. An open-type impeller lets trash pass through quite easily.

The double-suction volute centrifugal pump was used widely in early drainage plants. The Francis-type impeller, with curved vanes, is particularly efficient for lifts of 15 to 25 feet. Centrifugal pumps have a long life and are dependable. Usually they have a greater capacity than the same size screw or mixed-flow pumps, especially against the higher heads.

The deep-well turbine pump is used in irrigation. Most wells are 30 to 100 feet deep. This pump has three parts, the head, the pump bowl, and the discharge column. A shaft from the head to the pump bowl drives the impeller. It has a screen to keep coarse sand and gravel from entering the pump. The impeller is set near the bottom of the well. It forces water up through the discharge column to the surface. Most pumps of this type range in capacity from 300 to 1,500 gallons a minute.

Speed adjustment should be obtained for pumps that operate under variable lifts to obtain highest efficiency. Drainage pumps should be slowed down when operating against lower heads. Most small electric installations do not justify speed adjustments because the first cost of the necessary equipment is high. For pumps used a great deal, however, a speed adjustment is desirable for efficient operation at lower lifts. Sometimes two electric motors are set on the same shaft and operate at different speeds to provide speed regulation. Belt-connected units may have pulleys of different sizes for pump and motor to adjust the speed. Internal-combustion engines may be slowed down at low lifts and provide satisfactory speed regulations.

Direct-connected pumping units have an advantage over belt-connected units because the power losses due to transmission of the power are eliminated. The direct-connected unit is more compact. Transmission equipment is required if the engine or motor and the pump operate at different normal speeds. V-shaped belts and leather belts are the usual types. Chain and gear drives are sometimes installed. Proper alinement of the pump and engine is important. Properly adjusted belts have an efficiency of 95 to 98 percent if the alinement is correct.

In the larger drainage plants, it is wise to have two or more pumps for protection if a breakdown or emergency occurs. A variable rate of pumping is highly desirable in large plants, particularly when the runoff is low. A desirable range of pumping rates is obtained by having one pump half the capacity of the other unit. In large plants that drain several thousand acres, three units of equal size provide a desirable range.

The size of the pump may be computed in a preliminary way on the basis that the water will discharge at the rate of 8 to 10 feet a second through the pump discharge. Then the maximum daily runoff to be pumped needs to be determined. A considerable difference exists in the capacity of plants for the different localities. The required size is determined best by observing the conditions under which pumps are operating satisfactorily and furnishing the desired drainage.

The static lift is the difference of elevation between the water in the suction bay and the water in the discharge bay if the discharge pipe is submerged. If the discharge pipe is not submerged, the static lift is the difference in elevation between the center line of the water in the discharge pipe at the high point of discharge and the elevation of water in the suction bay.

The total head on the pump is the equivalent in feet of water of the total pressure the pump is acting against. It is equal to the static lift plus friction and other losses in the piping system.

Such losses include the entrance loss where the water enters the suction

pipe, the friction losses through the suction and discharge pipes, losses due to trash or obstructions in the pipes, losses caused by air entering the discharge pipe where it is under vacuum, and the loss of velocity head at the end of the discharge pipe.

In planning pumping plants to operate efficiently and in estimating costs, it is especially important to determine the maximum, minimum, and average static lifts for the pumps. The pump manufacturer will need that information in order to supply efficient equipment. The static lifts will control the selection of the type of pump. The axial-flow, or propeller, pump is adapted for total heads ordinarily less than 10 feet. Mixed-flow pumps can operate efficiently at heads from 6 to 26 feet. Centrifugal pumps may be designed for efficient pumping against total heads exceeding 12 feet.

The range in lifts that will be encountered is of primary importance in determining the maximum size of the motor or engine. The maximum horsepower required to drive a pump varies according to the pumping lift. The horsepower for the centrifugal pump is generally at a peak at a lower lift and tends to fall off at higher lifts. For a propeller pump, on the other hand, the brake horsepower required tends to increase as the lift increases. A survey to determine the required lifts under the whole range of pumping conditions is essential in order to plan efficient pumping equipment.

CHARACTERISTIC CURVES are the usual means of showing pump performance. Such curves generally show discharge expressed in gallons per minute (g. p. m.) plotted against total head (feet); brake horsepower (b. hp.), plotted against discharge; and pump efficiency (in percentage), plotted against discharge. The three curves are shown for each speed if the pump operates at more than one speed.

The discharge of drainage pumps declines as the total head increases if the speed is constant. The discharge increases as the speed increases if the total head is constant. Impellers are designed to obtain maximum efficiency at a specified head and speed. The efficiency drops off at both higher and lower heads than specified if the speed is held constant. The brake horsepower required to drive the pump depends upon the design and efficiency of the pump.

Drainage pumps usually may be furnished with the maximum efficiency at somewhat more than 80 percent. A well-designed pump should have an efficiency above 70 percent over a wide range of operating lifts. Pump installations sometimes are supplied by a manufacturer according to the purchaser's specifications as to the requirements at maximum and other operating lifts. The manufacturer generally supplies a set of characteristic curves. Most manufacturers base such curves on factory tests of the pump or on the tests of a similar pump.

Pump efficiency is computed by this formula:

$$e = \frac{\text{g. p. m.} \times H_t}{\text{b. hp.} \times 3960 \times e_t}$$

In the equation: e is pump efficiency, g. p. m. is gallons per minute, H_t is total head on pump (feet), b. hp. is brake horsepower (output of motor or engine), and e_t is transmission efficiency of belt or gear connecting engine or motor and pump (ratio, i. e., 97 percent equals 0.97).

For units in which the pump is connected directly to the motor or engine, e_t is 100 percent, and b. hp. equals the horsepower input into pump shaft. For belt-connected units, e_t varies from 95 to 98 percent, and only a small loss of power results.

DISCHARGE PIPES in most large drainage pumping installations should go over the levee near the high water level. If the pump is not submerged, the end of the discharge pipe should be below the low water stage of the discharge bay so that the pump may be primed easily. This arrangement of the discharge pipe permits a siphon action in

the discharge pipe, which reduces the total head on the pump. The siphon action has the effect of reducing the power used for pumping. It is important to obtain full benefit from the siphon action if a pump operates a high percentage of time. If the discharge pipe is submerged, it is desirable to install an automatic flap gate on the end of the pipe to prevent backflow through the pump when it stops.

An alternate arrangement is to have the discharge pipe above high water in the discharge bay. Such an arrangement is less efficient, but it is ordinarily used in small plants in combination with a submerged pump. The need for priming equipment thus is avoided, and it is a safe and practical arrangement for automatic operation; no backflow occurs through the pipe when the pump stops.

The friction losses in the suction pipe should be reduced by expanding the pipe so that the entrance area of the pipe will be 2 to 4 times the area of the pump flange. A rounded entrance of the suction pipe is recommended. The expansion of the suction permits the suction bay to be pumped low without causing the pump to lose its prime.

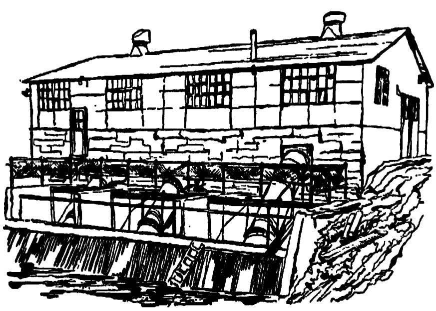
The discharge pipes of larger pumps usually should be 2 to 6 inches larger than the pump flange. The transition should be made by a short expanding section. Expanding a submerged discharge pipe at the end will improve the plant efficiency at small cost.

The friction loss measured in tests of suction and discharge pipes was 1.9 to 4.3 feet, based on 10 feet per second per velocity at the pump flange. The friction loss is a substantial proportion of the average static lift of pumping plants.

THE LOCATION of the pumping plant depends largely on the topography of the area and the location of the outlet in which the pump is to discharge. If several locations are possible, foundation conditions, construction of drainage ditches, and nearness of roads, living quarters, and powerlines may determine the site.

A site should be selected where stable foundation material— as shown by soil borings—is located. The foundation soil should be good because of the vibration set up by large pumping plants. A good foundation is a safety factor during flood conditions. Some large pumping plants have been destroyed by levee breaks because of quicksand or other unstable material near the plants.

The buildings for the pumping vary according to the type of installation, size, type of power, soils and foundation conditions, and the owners' desires. Many drainage districts have attractive, fireproof buildings of masonry



and steel, resting on piling. Some landowners have set pumping units on skids on the ditchbank with little or no housing. Because of the large volume of water that passes through drainage pumping plants at high velocity, a substantial foundation and well designed suction bay are necessary to prevent undermining of large plants. The smaller the plant, the greater is the choice in such construction, because erosive forces are less. A small, substantial, fire-resistant building is a good investment even for farm pumping plants—it protects equipment and keeps children and trespassers away from the pumps.

In most mineral and organic soils, piles are recommended for large installations. If the foundation is in clay or other stable material, spread footings may be used for small units and the construction costs will be considerably less than if piles are used.

The piling should support the walls

of the suction bay, wing walls, foundations of engines and motors, and building walls.

The suction bay is often used as the foundation for the pump or the pump and motor. It often consists of a rectangular pit enclosed on three sides by concrete walls. The pump may rest on a steel beam with a vertical suction pipe extending down in the suction bay the necessary distance below low water. This arrangement is satisfactory for vertical-type submerged pumps and for pumps which are set above water and require priming. Another arrangement is to set the pump at the side of the suction bay. Ordinarily the suction pipe enters the pump horizontally and curves downward into the suction bay. Electric motors may be set with the pump on the beams spanning the bay. Diesel engines should rest on a substantial foundation, which adjoins the suction bay.

The pump or suction pipe should be submerged an adequate depth in order for the pump to operate efficiently. In the preliminary plans, a submergence of 3 feet below normal low water pumping level may be assumed for sea-level pumping. If the pump is at 1,000 feet above sea level, the minimum submergence should be increased to 4 feet. Those figures should be modified on the manufacturer's advice, based on requirements of the pump.

The minimum clearance between the pump and side walls or suction pipe and side walls may be computed as 1.5 times the pump size. For example, a 10-inch pump requires a minimum of 15-inch clearance from the side walls, but here, too, the manufacturer's recommendations should be followed. The minimum clearance between the suction edge of the pump and the floor of the intake bay may be designed equal to the pump size if the manufacturer's recommendations do not specify otherwise. For example, a 10-inch pump requires a 10-inch clearance between the bottom of the pump or suction pipe and the floor of the suction bay.

Water storage at the suction bay is advantageous. The suction bay should be controlled within small limits to provide a more constant operating condition. If the storage available at the suction bay is quite small, the pumping plant will draw the water down rapidly under ordinary conditions and pumps will take air and operate less efficiently. The pumping lift would be increased, and frequent starting and stopping of the pumps will be required. A large storage at the suction bay will frequently make it possible to eliminate night operations and may result in lower labor costs.

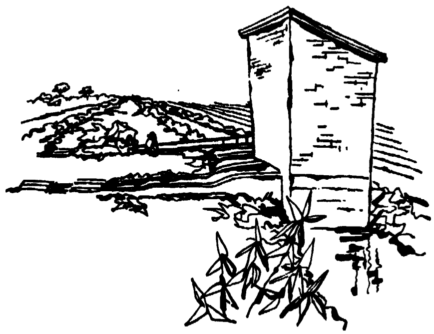
A special consideration may also be off-peak pumping rates, which lower costs if pumping is done at slack hours. A large storage helps users to take advantage of them. If large areas are to be drained, it is often desirable to leave a few low sloughs undrained in order to provide storage. Usually it is wise to excavate the main ditch leading to the pumping plant deeper and wider than necessary to provide the storage.

Automatic operation is feasible if electric power is used—particularly in the operation of small plants to save expenses. A float starts the motor when the water in the suction bay rises to a predetermined elevation. The pump then starts and gradually lowers the water and float. The water is pumped down to a level; the float trips a switch and cuts off the motor. Another way is to use an upper and lower electrode, which activate switches that start and stop the pump.

If the suction bay is likely to freeze, special precautions are needed. A vertical pipe filled with oil in which the float operates may be connected so as to reflect the stage of the suction bay. The float may operate in oil in below-freezing weather. Usually in very cold weather not much pumping is required, and manual operation of a plant is satisfactory with the float or electrode removed from the water.

Pumping tests should be obtained if the purchaser buys equipment on the basis of guaranteed efficiency. Most

manufacturers can test pumps at the factory before shipment. Field tests are costly but may measure efficiency of the completed plant, including the effectiveness of pipes and the pump.



Well-planned farm drainage pumping plant with pump discharging into concrete chute.

PUMPING PLANTS on small farms usually are installed with first cost as a main consideration. Inexpensive foundations and a minimum of equipment are installed.

In many places farmers can drain fields economically by pumping. The outlet ditches in many drainage enterprises are not deep enough to provide adequate drainage for low fields; it often is more economical to install small pumping units to drain the low areas than to construct deeper outlet ditches. Another example is the low land near the Great Lakes. High lake levels often impair outlets and crop losses result from poor drainage, and low dikes and small pumping plants have given many farmers good drainage.

Such pumping plants usually are simple and not overly expensive. Most of them cost less than 5 dollars an acre a year to operate, including interest and depreciation. The volume of water they handle is small, and large erosive forces are not set up in the suction and discharge bay, as with the large plant. Small pumps often are set on a sloping bank or suspended from beams across a ditch and have no permanent foundation and wood housing. Tractors may be used to drive them.

Farm pumping plants consisting of one vertical submerged pump with a free discharge are used extensively. They do not require priming equipment and can operate automatically if electric power is available. Many powerlines can handle motors up to 7.5 horsepower. That limits low-lift pumps to about 2,000 gallons a minute.

The capacity of farm pumping plants may be computed as follows: Required pump capacity equals required capacity of open ditch plus seepage minus storage.

The required capacity of open ditches is given by curves showing drainage coefficients for various crops and land areas, and may be obtained from the soil conservation district. Seepage may be an important factor if open ditches touch sand or gravel layer near lakes or rivers. Under such conditions seepage may be 0.1 to 0.5 inch each 24 hours over the entire watershed area. Seepage generally may be disregarded if the ditches are in clay or silt soils. Storage is the capacity of the suction bay, sloughs, ponds, and ditches to store water between normal water level and high water level. It is assumed that this storage will be effective in a 24-hour period.

Most drainage plants in the upper Mississippi Valley draining agricultural land are used for field crops and plants draining fewer than 3,000 acres have been designed from 0.75 to 1.5 inches runoff. In places where truck crops or high-value crops or property are to be protected, a higher capacity—even up to 4 inches from the watershed in 24 hours—should be provided. Greater capacities are required for small areas in Louisiana and Florida.

JOHN G. SUTTON, *a drainage engineer, joined the Washington staff of the Soil Conservation Service in 1939. He entered the Department of Agriculture in 1925. Among his other field assignments was a 5-year study of design, operation, and costs of drainage pumping plants in Illinois, Iowa, and Missouri.*

Drainage of Peat and Muck Lands

John C. Stephens

Peat and muck soils have unique biological, physical, and chemical properties, and on them the common drainage and management practices that are used on mineral soils are not suitable.

Biologically the organic soils support hosts of micro-organisms, mostly bacteria, which are largely responsible for the formation and alteration of the peat. The action of the anaerobic micro-organisms builds up the organic soils. The aerobic organisms are largely responsible for decomposition.

The soils have a dark color, light weight, and an absorptive, spongelike texture. They have high absorptive and radiant properties, a high heat capacity, and low heat conductivity. They burn at relatively low temperatures and have a high cation exchange and a high buffer capacity, which strongly resists changes in acid reaction. Peats tend to be acid, but range from pH 3.5 to 8.0.

The peat and muck soils cover an estimated 80 million acres in the United States, mostly in the cool, temperate, humid region of Maine, Massachusetts, New York, and New Jersey, and the Great Lakes States of Michigan, Wisconsin, Minnesota, Illinois, and Indiana. Minnesota, Wisconsin, and Michigan have about 75 percent of the total peat and muck lands in this country.

Large bog deposits exist in the warm-temperate, humid region within the southeastern coastal plain swamps of Virginia, North Carolina, and Georgia, and along the coastal marsh tidelands of Louisiana and Texas. The subtropical, humid region of Florida, including the Everglades and related localities, make up 14 percent of the total national deposits. Other deposits, in the Pacific coastal area, include the California delta peats, formed where the climate is hot and dry, and the semiarid to subhumid marsh and valley deposits in Washington and Oregon.

The Everglades, more than 2 million acres, is the largest known tract of peat and muck soils in the world. Other large tracts occur in the delta area of California, along the coastal marshes of Louisiana and Texas, and in Michigan, Minnesota, and Wisconsin. The bulk of peat and muck lands, however, are in small pockets of 1 acre to several hundred acres scattered over thousands of farms. The deposits are valuable for crop production, water reservoirs, and wildlife refuges, and as a source of organic materials.

Peat and muck soils, however, vary widely and some of them hold little in the way of ordinary agricultural possibilities. Efforts to reclaim them often have failed because the soil was poor, they were far from markets, and they were subject to frosts. On the other hand, proper management of the good, well-situated lands has been successful, and the better soils near city markets may be valued at a thousand dollars or more an acre.

Besides crop production, 256,000 tons of peat were used in the United States in 1950—63 percent for soil improvement, 22 percent in mixed fertilizers, 12 percent for poultry litter and stable bedding, and 3 percent for miscellaneous purposes. The organic soils are also potentially a source for fuel, producer gas, and for basic organic chemicals produced by distillation and carbonization. The total value of peat and muck lands in the United States has been appraised at approximately 40 billion dollars.

PEAT AND MUCK have been created from the vegetation of bogs, marshes, and swamp forests, or from sphagnum mosses, by the action of micro-organisms, largely bacteria.

Soil technicians define peat as a soil that has less than 50 percent of min-

eral matter, on a dry weight basis; muck as a soil having 50 to 80 percent of mineral matter; and mineral soils as those having more than 80 percent of ash after burning. Peat soils are only partly decomposed and retain a fibrous or granular texture. The mucks are thoroughly decomposed and are finely textured, uniform, amorphous, and black.

The principal types of peat are sedimentary, fibrous, woody, and sphagnum. The first three are formed in basins or on poorly drained lands. The sphagnum moss type may develop on higher land.

Sedimentary peats are derived primarily from submerged, succulent, open-water plants, such as naiads and pondweeds, which contain relatively small proportions of cellulose or hemicellulose materials. These may be mixed with algae, and dead micro-organisms, with fallen pollen and leaves from the higher plants, together with wind or waterborne mineral sediments.

Fibrous peats are composed of the remnants of reeds, sedges, and related marsh plants, which grow in shallow water along the edge of marshes. The fibrous peats contain a reasonably high proportion of cellulose. The water-holding capacity of the fibrous peats is high, and the water transmissibility is satisfactory. They are less acid than the moss peats and have a more desirable texture for tillage than the sedimentary peats. They contain from 2.0 to 3.5 percent of nitrogen. Many of the fibrous peats are suitable for agricultural purposes.

Woody peats are formed from the climax vegetation in swamp deposits. They develop from the residue of trees and shrubs which occupy the forest floor of the swamp. Ordinarily less calcium and other minerals reach the woody peats. Thus they are normally more acid than the fibrous type. Woody peat has a lower water-holding capacity than fibrous peat, and when drained provides a loose, granular and blocky structure, through which water moves readily. This soil has excellent tilth and usually is rated intermediate between fibrous and sedimentary peats as a field soil.

Studies of ancient climate indicate that the last continental glacier reached its greatest advance about 11,000 years ago and slowly retreated for 5,000 or 6,000 years to its present position. Thus, we may assume that the peat deposits which were laid down in depressions resulting from the last glacial retreat are younger than 10,000 years. The age of some of the northern deposits ranges from about 2,500 to 8,000 years. The Everglades peats of Florida appear to have developed over the past 5,000 years.

In Maine, Washington, the Great Lakes States, and Canada, moss peat is formed. Cool, damp weather favors the development of the deposits. Extensive areas also occur in northern Europe. This peat is formed principally from sphagnum mosses and associated vegetation, which depend on rainfall, dews, and fogs for moisture.

The sphagnum peats can hold up to 15 or 16 times their weight of water and absorb moisture to the extent that they actually lift the water table above the surrounding country. They build up by layers and sometimes reach a thickness of 30 feet. Customarily they present a dome-shaped surface profile. Soils formed under these conditions are commonly termed high-moor peats. They are extremely acid—pH 3.5 to 4. They are not readily decomposed.

This type of peat is a poor medium for the growth of organisms causing decomposition, and the nitrogen content is low. Even when drained it is a poor soil for the growth of the higher plants, unless the acidity is corrected by the heavy use of lime, and a complete fertilizer, including nitrogen and the microelements, is added. Even then, several years may be required to build up a population of soil organisms suitable for growing crops. Its principal uses are for the improvement of other soils, for packing plants and flowers, as an absorbent litter for stables and poultry

houses, and for related uses where its high water-holding capacity is of value.

A UNIQUE FEATURE of organic soils must be considered before their reclamation is begun. Peat and muck lands are subject to subsidence—they lose surface elevation — when they are drained. The subsidence is caused by shrinkage due to drying, loss of the buoyant force of ground water, compaction, slow oxidation, burning, and wind erosion.

The average subsidence rate in the Everglades has been about 1.25 inches a year, and 50 years of drainage has resulted in the loss of some 40 percent by volume of the better agricultural soils. The organic soils in the Sacramento-San Joaquin delta area in California are reported subsiding at the rate of approximately 3 inches a year.

In virgin organic soils, loss in elevation is most rapid immediately following drainage and cultivation. The loss varies with the firmness of the peat and its structure. Sedimentary peats may lose as much as three-fourths of their drained volume very rapidly. Fibrous and woody peats ordinarily lose much less. Before cultivation, most fibrous peats have practically the same density from top to bottom, but in 5 years or more of tillage the top 18 inches increase in density to about double that of the peat underneath. The cultivated layer changes into an amorphous mass, the color darkens, the seepage rate declines, and the peat is transformed into a mucky condition. The increase in density brings a corresponding loss in volume.

As drainage continues, the rate of subsidence levels off to a slow, steady rate. The loss continues as long as the land is drained, and is due to slow oxidation caused by the action of aerobic micro-organisms in converting organic matter into carbon dioxide and other gaseous products. The rate at which the soil is consumed depends primarily on the depth of water table for a given soil type.

S. A. Waksman and his coworkers at Rutgers University found that the action of destructive bacteria was highest in the drained, low-moor peats and lowest in the extremely acid, high-moor peats. When the acid peats were treated with lime, manured, and put under cultivation, however, the micropopulation increased to about the same as that in the low-moor peats under similar drainage. Working with samples of low-moor peats, the investigators determined that the moisture content controlled the speed of decomposition. A moisture content of 50 to 80 percent of the total moist weight of the peat gave maximum rates of decomposition. Above and below that range the rate rapidly diminished. Some 20 percent of the dry weight of the original peat sample was decomposed at a moisture content of about 70 percent in 19 months; most of it was lost into the air as carbon dioxide. The organisms were active only when soil temperatures remained above 40° F.

Peat and muck water-table plots were established at the Everglades Experiment Station of the University of Florida near Belle Glade and at the Muck Crop Experiment Station of Purdue University at Walkerton, Ind.

It was discovered that the subsidence depended mainly on depth of the water table but that the rate in Indiana was a little less than one-half that in Florida. For average water-table depths of 12 inches, 24 inches, and 36 inches, the corresponding annual subsidence rate was approximately 0.6 inch, 1.4 inches, and 2.3 inches in the Everglades; and 0.1 inch, 0.6 inch, and 1.1 inches in Indiana. The plots were on soils that had already taken their initial shrinkage. In the Florida experiment, the prescribed water table was held all year; in the Indiana experiment, it was held only during the crop year from May to September.

Reference plates set below the permanent water table at the Everglades station showed that all soil shrinkage occurred above the water table. Studies of volume and ash indicated that

the lowering of the surface on those plots could be attributed only slightly to compaction and was caused largely by oxidation.

On drained lands not cultivated or grazed, the drained zone develops an open, spongy texture, which allows free aeration. When such soils are plowed later, the loss of soil mass has been greater than the loss from adjacent tilled lands under the same water levels. It is assumed the compactness caused by cultivation inhibits aeration and retards oxidation. Hence, drained lands of this class should be put into use immediately.

Organic soils will burn when dry. Careless and uncontrolled burning destroys large areas each year. A peat fire is hard to put out and will burn until the soil is saturated by rainfall or by flooding. Burning reduces the soil depth and may leave the ground in an uneven, pitted condition that is unsuitable for farming.

Blowing, which removes soil and injures tender plants, is a problem in clean-tilled organic soils, especially right after cultivation when the surface is dry and powdery. Wind losses can be reduced by maintaining proper soil moisture and using a heavy corrugated roller, which leaves a ridged surface. Windbreaks are used in some muck areas to deflect the air currents and reduce soil movement.

THE MOST PRACTICAL way now known of reducing the loss of peat and muck soils is by controlled drainage that holds the water level as high as crop and field requirements permit before drainage.

The first step is to determine if the quality of the soil is suited for the intended crops. The acid peats are less valuable for most farm crops than the high-lime soils. Such special crops as cranberries can be grown on the acid peats. Some soils can be made productive by adding lime, but the peat colloid complex is naturally acid and much more lime is needed to raise the pH of a peat, as compared to a mineral soil. Many crop failures have resulted from attempts to develop the acid peats for crops to which they were unsuited. A simple test of acidity would have forestalled such ill-advised ventures.

Fibrous and woody peats generally are better for agricultural use than the sedimentary and moss peats. Mucks contain mineral admixtures, which are more likely to supply potash, phosphate, and the microelements necessary for plant growth. They tend to be more fertile than the peats.

The effectiveness and cost of measures to control surface and soil water may be largely determined by the depth and type of the peat or muck and the kind of underlying rock or subsoil. If the underlying material is hard rock or otherwise untillable, the depth of the organic soil should be at least 3 to 5 feet to justify drainage because of eventual subsidence.

Soft organic soils, such as the sedimentary peats, will have a greater incipient shrinkage loss than the firmer fibrous or woody peats. In virgin peats intended for cultivated crops, a minimum depth of 5 feet is desirable. Firm peats that have taken their initial shrinkage and land intended for use as permanent pasture should be at least 3 feet deep to warrant development.

If the peat or muck overlays fertile, tillable soil, the situation is quite different; then even shallow bogs may be recommended for cultivation. Minimum depths of organic soil may be ordinary plow depths if the subsoil, such as a shelly sand, is rich in lime, which is considered desirable.

If a permeable substratum near the ground surface is capable of carrying a large flow of water, dikes and ditches are ineffective in cutting off inflow from outside lands, and it will be difficult to hold different water levels in the same or adjoining fields. In moderate to shallow soils, where the field ditches cut into the permeable stratum and peripheral water levels are not too high, however, subdrainage will be good, and spacing of the field drains can be increased for drainage and subirrigation.

If the permeable beds act as artesian aquifers to bring outside water under pressure into the developed tract, special drainage methods involving relief wells may be required.

If the subsoil is a nonpermeable material, such as a plastic silt or clay, there will be relatively little seepage, but closer spacing of field drains will be required.

On drainage projects where roads must be built and foundations secured for water-control structures, their cost will depend largely on the suitability of the substrata.

Besides the inherent chemical and physical nature of the soil and the character and depth of the substratum, the value of the organic deposit is influenced by the location, topography, and water supply. It should be located close to existing roads and markets so that transportation costs will not be exorbitant. It should be situated so that outfall drainage, either by pump or gravity, is feasible at reasonable cost. The tract should be level enough so that a system of water-level controls may be installed economically. A source of irrigation water for maintaining proper soil moisture is highly desirable.

All those factors should be considered in the preliminary investigation to ascertain whether a favorable cost-benefit ratio appears to be forthcoming before making detailed plans for drainage. The same principles hold for the evaluation of cost-benefit ratios for the drainage of organic soils as for mineral soils. It should be kept in mind, however, that the organic soils have limited life, productivity varies to a great degree with the soil type and crops grown, and income from specialized crops fluctuates widely with market conditions.

IF THE PRELIMINARY investigations indicate that proper water control is feasible, that the soil is suited for the desired use, that the improved land can be used to immediate advantage, that the venture will have a high cost-benefit ratio, and that development can be properly financed, the prospective developer may want to get a detailed plan for reclamation.

The scope and cost of such plan will vary with the size and complexity of the project. On small areas the advisability of development may depend not so much on the land itself but on the experience of the farmer in handling organic soils and whether the crops suited for the soil will fit into his farming system.

On large projects the planning should be done by engineers experienced in drainage of peat and muck soils. The scope of the investigation might well include: Drainage and agricultural history; market facilities and income statistics; crop and vegetative requirements; longtime records of rainfall, evaporation, and temperature; geologic and ground water conditions; topographic surveys; soil surveys and physical land conditions; water control recommendations, including drainage and irrigation requirements with design rates and plan of control works; construction estimates and costs; maintenance recommendations and costs; total cost summary and cost-benefit ratio; financing methods; and annual cost assessments against benefits.

ONCE THE VENTURE of reclaiming a bog deposit has been decided upon, the first requirement is removal of excess water. The best time to start drainage normally is the driest season. First the inflow from adjacent lands should be blocked off and surface water removed to dry out the land enough for clearing and installing the drainage system. On ground subject to inundation (because there is not enough surface relief for proper drainage) or on ground subject to frequent overflow from nearby lakes or streams, protective dikes must be built around the area and pumps provided to remove the water.

In building the dikes it is best to use mineral soils—not peat—where practicable. Sometimes organic material

may be added to sandy soils to reduce seepage through the dike. It may also increase fertility and aid in the growth of a vegetative cover to control erosion. Mucks high in mineral content and structurally stable often can be used to good advantage in dike work.

Frequently, however, peat will be the only material that can be used. In the Everglades, in fact, dikes of peat are often used to protect farms. The size of the dike depends on the difference in water levels inside and outside the shielded tract.

A dike built from the organic soils requires a larger embankment than one built from the heavier mineral soils. A well sodded, compacted dike of firm peat with a settled height of 5 to 6 feet, a bottom width of 15 to 20 feet and with side slopes of not less than 1:1 usually suffices to withstand water stages outside the dike up to a depth of 3 feet above land surface if the field water level inside is drawn down about 2 feet below the surface. If the dike is subject to wave action, a heavily matted sod on the dike and an offshore stand of willows or similar planting are desirable.

Dikes of fibrous peat will settle up to one-third of their original volume the first year. Sedimentary peats shrink much more. Allowances should also be made for slow shrinkage, after the first year, by oxidation. Sufficient soil should be left in the berm where it can be excavated and used periodically to build up the dike to keep it to grade.

Before the dike is constructed, it is desirable to remove the vegetation from beneath the base to assure a bond between materials. Also, to retard seepage and key in the bank, a trench about the width of a dragline bucket and 4 to 5 feet deep should be dug and backfilled with puddled organic soil. This puddle trench helps prevent leakage where the land has dried out and shrinkage cracks occur in the ground.

Shrinkage cracks may extend through the dike itself. A remedy is to shape, tamp, and sod a rough dike soon after the excess water has drained. If the soil is a sedimentary peat or a muck containing marl or any colloidal admixture that causes the material to slump, the soil may have to be excavated and allowed to drain before the dike can be shaped and completed. Sodding reduces maintenance by retarding subsidence and preventing wind erosion and rank growths of weeds.

Draglines or dredges are commonly used to construct dikes. The material should ordinarily be taken from outside the field, and an ample berm of undisturbed soil left between the dike and borrow channel. The water pressure outside the protected area then will be less apt to cause structural failure, the outside channel will serve to divert and allow the ponded water to escape faster, and the ditch will act as a firebreak.

The need for farm roads should be kept in mind when laying out the dike system, but using peat dikes for roadways lowers the dikes and makes them more subject to wind erosion. Dikes that are capped with rock or other suitable material are more stable and more usable as roads.

If a sluggish stream causes boggy conditions, surface drainage may sometimes be accomplished by straightening and increasing the size of the channel without diking. Before such a remedy is adopted, however, backwater flood stages, resulting from downstream obstructions, should be ascertained, and it should be remembered that the bog surface will subside with drainage.

In places where swampy conditions are caused or made worse by seepage of ground water, the problems of drainage are more complex, and the advice of a ground water geologist should be sought before costly reclamation work is undertaken. Seepage from surrounding uplands through the soil mantle may often be intercepted and diverted by cutoff trenches before it reaches the peat or muck area. If seepage is carried beneath the bog by a confining layer and then reaches the surface through

a leaky roof, control measures are often expensive; although, where the rate of flow is moderate, relief wells have been used successfully. In many instances seepage, if it can be controlled, may be helpful during dry periods to supply water for irrigation.

ONCE THE LAND has been shielded from outside water, the next step is provision of field drainage. Soil that is very wet and spongy may require several seasons of progressive drainage before all the water-control facilities can be installed.

First, the main ditch leading from the pump, or other outfall, should be dug, the work proceeding upstream into the tract to be drained. Branching off from the main ditch, adequate laterals and open field drains should be constructed to dry out the land enough to proceed with the clearing and initial plowing.

The amount of labor required to bring the land under cultivation varies according to the native growth. Trees must first be cleared. Then it may be advantageous to put the area into pasture for several years to allow the stumps and roots to decay so they may be more easily removed.

If the ground is covered with grass, the first step is breaking. Light burning is permissible if it is done when the land is wet and the soil is not harmed. Initial breaking should be deep and done with a 24-inch plow if practicable. The land then is rolled with a heavy roller.

On raw, virgin peats, the land should be pastured. If drainage is good, the soil should be broken in with such crops as peas, oats, barley, or other coarse-seeded plants. It is suggested that the land be leveled as much as feasible in the early stages of development. It is ordinarily good practice to provide deep drainage for several years to improve the physical condition of the soil by aeration before the permanent water-control structures are installed.

The highest subsidence losses will occur immediately after the initial drainage and cultivation. The hydraulic design should be determined with respect to the anticipated surface elevation. The amount of initial subsidence to be expected will depend in large degree on the type of peat and past drainage history. Firm, fibrous peats may be expected to sink 12 to 24 inches during the first 5 years of tillage. The flaccid sedimentary peats often shrink up to three-fourths of their drained volume. An allowance of approximately 30 percent of the peat depth is suggested for newly drained sites and about 10 percent for previously drained agricultural areas. The annual subsidence rate after the first 5 years will depend on depth of drainage.

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THE DESIGN of the drainage system must consider the selection of the proper runoff rate for the tract; the best layout of field drains to secure adequate soil drainage throughout the cropped area; and the problem of holding water levels at the correct depths for maximum crop yields, control of subsidence, and protection against frost.

Runoff requirements for organic soils depend on the frequency and intensity of the rainfall, the storage capacity of the soil, the value of the crops, and the sensitivity of the plants to immersion.

Plants are drowned when the root system is smothered and gaseous exchange is prevented. Oxygen normally is absorbed by the roots in exchange for carbon dioxide, which is cast out. Different plants vary greatly in their oxygen requirements, but the demand usually rises in response to such factors as sunlight and high temperature, which increase physiological activity. Thus crops tolerate flooding longer after a storm, when the weather is cool and cloudy, than when it is hot and sunny. Some plant roots can stand submersion better when there is a movement of the ground water, which can dissolve and remove the carbon dioxide and help supply the oxygen demand.

H. A. Jongedyk and his associates, who investigated controlled drainage of truck and field crops grown on muck soils at Purdue University, concluded that a safe rate of storm removal would be a reduction in the ground-water level to a depth of 18 inches beneath the surface within 48 hours. They found that once the water level is that deep the urgency of additional drainage is reduced considerably.

In the selection of the drainage modulus—or runoff rate—the intensity and frequency of the rainfall are usually the most important elements.

It is not considered practicable to install farm drainage systems that will dispose of the maximum rainfall, and it appears to be good management to plan on losing a crop about once in 5, 10, or 15 years, the interval selected depending on the value of the crop that might be saved as balanced against the increased cost of providing additional drainage for very infrequent storms. In regions where intense rainfalls are frequent, the drainage system should be arranged so that at least part of the farm can be drained adequately during any storm by locating dikes and control gates with which runoff from other parts of the farm can be delayed when desired. Crops on at least part of the farm can be saved in that way.

The general opinion among growers in the Everglades is that facilities to remove 2 or 3 inches in 24 hours should be available on truck farms and 1 inch on cane and pasture lands. In the New York area, it is considered feasible to provide pumping capacity for 1 to 1.5 inches for high-value crops. In Indiana 0.37 to 0.5 inch a day seems satisfactory for meadow and pasture, 0.75 to 1 inch a day for field crops, and possibly as much as 2 inches for truck crops.

In districts where local requirements are not known, a handy guide for truck-crop drainage is to determine the frequency period for which protection against crop loss is economically justified and to plan on caring for the rainfall from a 2-day storm for the selected frequency period.

Technical Report 5 of the Miami Conservancy District, *Storm Rainfall in the Eastern United States*, revised in 1936, contains the results of frequency studies for excessive precipitation in the United States east of the 103d meridian. The maximum rainfall recorded up to 1932 during periods of 1 to 6 days in each quadrangle of 2° is given. Isopluvial charts also show the amount of rainfall that might be equaled or exceeded at any given locality in periods of 1 to 6 days, with a frequency of once in 15, 25, 50, and 100 years.

Miscellaneous Publication 204 of the Department of Agriculture, *Rainfall Intensity-frequency Data*, represents a series of 56 charts of the rainfall-intensity frequency relation for the entire United States for periods of 5 minutes to 1 day. Where the 2-day frequency is not available for the recurrence period desired, a close estimate can be obtained by adding 12 percent to the 1-day data in the bulletin.

The damage from excessive rains may be reduced somewhat by the high absorptive capacity of organic soils. The available soil water storage will vary with the depth of the water table, the moisture equivalent, and the time since the last rain. Under average conditions, where the water table averages about 2 feet deep before a storm, however, it may be estimated that 1 inch of rain will raise the water table about 6 inches, or that about 4 inches will be required to saturate the soil.

To illustrate the method of computing the drainage modulus: Assume a truck farm in the Everglades where the water table is held at a depth of 24 inches, there is no seepage inflow, and the crop justifies a protected frequency period of 10 years. From rainfall records at the Everglades Experiment Station, it is found that the 48-hour rainfall-expectancy rate for a 10-year interval for the 5-month period, November through March, which is the normal growing season for vegetables in this district, is 6.3 inches. Since the water level should be 18 inches below surface at the end of the 48-hour pe-

riod, a 6-inch depth is available for ground storage which allows a credit for 1 inch of rainfall. Then $6.3-1.0=5.3$ inches in 48 hours, or a required drainage modulus of 2.6 inches a day.

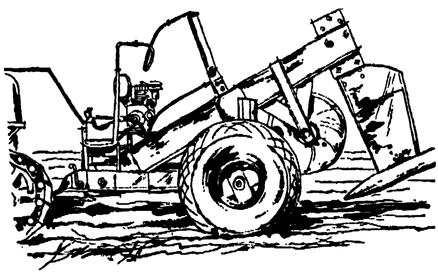
Again, assume a locality in the Great Lakes States, where local rainfall records are not available near latitude 43°, longitude 91°, and where the crop value justifies a crop-protection period of 15 years, with other factors remaining the same as before. From the isopluvial charts of the Miami Conservancy District, the maximum 2-day rainfall to be expected on the average of once in 15 years is 4.4 inches. The required 24-hour drainage modulus is $4.4-1.0=3.4$ inches in 48 hours, or 1.7 inches a day.

THE EXTENT to which field drainage is necessary depends on the proposed use of the land, the depth and internal drainage qualities of the organic soil, and the water-carrying ability of the subsoil. Reliance on open-ditch drainage alone or the incorporation of a tile system depends often on the acre-value of the crops that may be grown and the relative cost and convenience of the two types of drainage systems. In the firmer organic soils, mole drains can often be used to advantage in place of the more expensive tile systems. Their use in oozy peats or mucks is less successful.

In areas where there are no drainage patterns already established to furnish a clue, the layout of field drains is a perplexing problem. Proper spacing, as in the case of mineral soils, will depend largely on the effective permeability of the soil and the water-table requirements. Unlike mineral soils, however, soil moisture equivalents or laboratory classifications of permeability are of little aid in selecting proper drain spacing on peat and muck lands. On the other hand, field methods of determining effective permeability, such as the auger-hole method or the drain-function method, are of value in the hands of technicians.

Many of the organic soils can be cropped with only open-ditch drainage. No general rule can be given for their spacing, which varies from as close as 50 feet on some truck farms in the Great Meadows district of New Jersey to as far apart as 1,320 feet in the Florida Everglades. Widely spaced ditches can be used if the land has good internal drainage, especially if the soil is laminated by horizontal cleavage planes or the vertical drainage is good and the peat is underlain at shallow or moderate depth by permeable strata, which act as a horizontal aquifer to convey the soil drainage to the laterals and main drain. But muck soils with poor internal drainage, underlain by a silt, clay, or other impermeable subsoil, may require spacings too close to be practical. In fact, if the ground water movement is very sluggish, the practical drainage modulus allowable for the farm may be limited to the total flow that can seep into the field drains during the critical drainage period rather than be determined by the rainfall intensity.

Mole drains are a valuable supplement to open-ditch drainage where



they can be used. They aid greatly in equalizing water levels between ditches for both drainage and for subirrigation. Moling may be more effective in fibrous peats than in some of the sedimentary peats or soft plastic mucks. They are formed by drawing a bullet-nosed cylinder, 6 inches in diameter, through the soil to make a hole about 4.5 inches in diameter. The resulting mole drains should have a minimum depth of 30 inches below the surface to prevent closure of the holes by compaction during normal farming operations.

Mole drains are best established when the water table is below the proposed hole depth. Moles operating below the water table set up a partial vacuum, which tends to close the hole behind the bullet. The bullet draws a pressure of nearly 9 inches of mercury, the equivalent of about 11 feet of water, when operating 6 inches below the water table at normal tractor speed. The bullet should be vented to prevent this back pressure. Moling machines should not be pulled at high speeds; the slower the speed, the less tendency for the hole to close.

Mole drains are spaced 12 to 15 feet apart. Costs of moling in 1954 were 1 to 2 dollars an acre. Properly constructed moles in suitable soils should give effective service for 5 to 8 years. When they cease to function satisfactorily, new lines can be pulled in between the old drains.

Where the acre-value of the crop is high and soil conditions are suitable, tile underdrainage may be desirable. Such drains avoid cutting up the fields by ditches, save land area, eliminate open-ditch maintenance problems, and do away with weeds or sod along ditch banks.

The same general rules hold for installing tile systems in organic soils as in mineral soils, but several important differences must be borne in mind. Proper spacing, as for open drains, depends largely on the effective permeability of the soil and on requirements of the water table. Often the best intervals can be judged according to spacing used on nearby farms or observations of open ditches. Wide spacings may be tried first and additional lines added later if needed. Ordinarily lines are spaced 50 to 200 feet apart. The reed-sedge and woody peats usually drain well at spacings of 100 to 120 feet. If controlled drainage and subirrigation are used, close spacing of the drains is desirable to flatten out the undulations of the water surface between tile lines. If the surface soil has become dense and compacted and the vertical seepage is retarded or if extensive acreage is completely tiled, enough open ditches should be left to provide surface drainage during flash floods.

The gradient of the tile system will depend essentially on the slope of the land. When the field is to be subirrigated by reversing the flow in the system, the tile gradient should be held as low as drainage needs will permit. The minimum recommended gradient is 1 inch to 100 feet

Conventional flow formulas are used to determine sizes of tile, but standard tile smaller than 5 or 6 inches should be used with caution in bog soils, because small tile settle out of alinement easily and cause clogged lines. Long lengths of tile generally are preferred for peat and mucks, as they are more likely to stay in place. If it is necessary to lay tile in oozy soils the long, perforated type may be best.

The installation of tile should be delayed in fresh lands until several years of open-ditch drainage and cultivation have accounted for the heavy initial shrinkage losses. Then they should be installed as deep as feasible to allow for the slow subsidence of the surface caused by oxidation of the organic soil in the drained zone. A minimum depth of 4 feet is recommended; 6 feet is better where the subsoil and outlet conditions allow.

P. W. Manson and D. G. Miller, of the Minnesota Agricultural Experiment Station, found that the corrosive action on concrete varied with the acidity of a peat and the quality of the concrete. Rich mixes of high strength and low permeability gave the greatest resistance. All concrete drain tile installed in peat should be of at least the quality prescribed for extra-quality drain tile in standard specifications of the American Society for Testing Materials, designated C4–50T. Concrete in tile of this classification will have a compressive strength of 4,000 pounds to the square inch, or more, and an absorption of 8 percent or less. An organic soil with a pH value of 6.0

may be considered to be definitely acid. When that value drops much below 6.0, the use of concrete tile becomes a matter of doubtful economy. Clay tile that meet ASTM specifications are not subject to acid corrosion; both glazed and unglazed clay tile are satisfactory for use in organic soils regardless of the degree of acidity.

After the tile has been laid, special care must be exercised in blinding the tile line and in backfilling the trench to prevent puddling of the organic soil. When the soil is disturbed, water movement is greatly retarded.

B. S. Clayton, formerly of the Everglades Experiment Station, found that for vertical samples of Everglades peat the average depth of water passing through the top 18-inch layer which had been disturbed by tillage was 0.30 foot a day, that through the 18- to 36-inch layer was 27.3 feet, and that through a horizontal sample was 0.25 foot a day. The second vertical and horizontal samples were both from the undisturbed, brown, fibrous peat, and the wide difference of seepage rates through them is due to the structure of the partially decayed sawgrass residue, which provides small openings along vertical lines. The seepage rate through the top layer of soil was not much greater than that through the horizontal sample, because of structural changes by tillage. Thus, if the excavated peat, especially the dense plastic topsoil, is carelessly replaced around the tile, an impermeable ground water barrier that is formed will cut down seepage into the tile joints.

The joints of the tile should be covered with several inches of a porous material as gravel, cinders, or porous topsoil of mineral origin. Straw, sawdust, sod, or other organic materials may be used when they will be below the water table so that they are not subject to rotting. When the excavated peat cannot be replaced without causing a puddled condition, the trench should be backfilled with permeable material to within 12 or 18 inches of the surface before replacing the organic soils. If permeable material is scarce, vertical relief drains may be provided at intervals along the tile line to convey surface drainage downward to the depth of the blinding material.

Tile drains in organic soils sometimes do not work properly for several years. As the soil over the drains becomes aerated, plant roots penetrate the zone. As the plants grow and then die, the dead roots tend to leave open casts. Worms and organisms begin working in the live soil and improve the texture. Sometimes shrinkage cracks develop when the peat becomes dry and never completely close. During this time the permeability of the soil around the drain is improved by drainage to the extent that the tile serves effectively thereafter.

Drainage is essential for cultivation of peat and muck soils, but too much drainage will cause ruinous shrinkage and subsidence and make the soils undependable for crop production.

Each farm therefore needs a complete system of water control to provide drainage in wet weather and irrigation during dry weather. Control of ground water levels is desirable for attaining maximum crop production, for conservation of the soil, and for protection against frost.

Experience over the country and studies of drainage show that the best water tables for crop production in peat and muck soils vary with the rooting habits, maturity, and variety of the crop; the capillarity and water-holding characteristics of the soil; and the distribution of rainfall over the growing season.

The water-holding capacity of organic soils generally drops as the bulk density increases. For example, when they are near field capacity, Okeechobee muck, with a bulk density of 0.42, contains 30 percent water by volume; Okeechobee peaty muck, with a density of 0.29, contains 66 percent; and Everglades peat, with a density of 0.15, contains 75 percent. Ordinarily, the

more compact and denser the soil, the higher the capillary column will rise above the water table but the slower the water will be transmitted upward.

The organic soils are exacting in their requirements for a satisfactory supply of moisture for crop production. The maximum levels that can be held without harmful effects are slightly below the zone of dense rooting.

P. M. Harmer, of Michigan State College, learned that most farm crops in Michigan produce best yields on muck with the water level held from 30 to 36 inches during the summer, although it may be held somewhat higher during early stages of growth. He stresses the importance of maintaining a fairly uniform water table during the greater part of the growing season to prevent the development of a deep-rooted zone during low-level periods that would be damaged by a rising level. Among the crops that preferred water levels under 30 inches were hay, cauliflower, celery, cucumbers, lettuce, parsley, peppers, radishes, spinach, squash, swiss chard, beets, tomatoes, turnips, strawberries, cranberries, and blueberries. Crops requiring water levels deeper than 36 inches were barley, oats, mangels, rye, and wheat.

A. R. Albert and O. R. Zeasman, of the University of Wisconsin, state that nearly all the special truck crops need a rooting zone of 24 inches or more of drained soil for good yield and high quality and that no material decrease in the yield of the crops occurs with drainage depths down to 36 inches. A depth of 48 inches is suggested for corn.

Research at the Minnesota Agricultural Experiment Station showed no marked difference between the average optimum depth of drainage for field crops and for truck crops, according to H. B. Roe. An average drainage depth of 36 to 40 inches is recommended for general farming. On bogs devoted to grass crops, a depth of 18 to 24 inches is suggested.

At Purdue University, onions, carrots, sweet corn, potatoes, and mint were grown on plots with controlled water depths of 15 to 38 inches. No important differences in crop growth occurred in plots having a 24-inch water table or deeper. Plots with a 15-inch water table yielded less, and the quality of the crops was poorer than those grown on the deeper water tables. A satisfactory minimum depth of 20 inches for the crops listed was suggested.

Studies at the Everglades Experiment Station indicated a water table of 18 to 24 inches was best for most truck crops. Celery and onions seemed to do best at the 18-inch level. Beans, cauliflower, and potatoes did best at 24 inches. Corn and lettuce required deeper levels up to 30 inches. Pasture grasses produced well on water levels of 18 inches but did not suffer up to 36 inches. The tolerance of sugarcane was found to vary with the variety.

We can assume from the investigations that a water table of 24 to 36 inches is desirable for most field and truck crops, but that mint, celery, canes, and pasture grasses will do best at shallower tables of about 18 inches. Grains and corn may need water levels up to 40 inches for best results. In dry regions the levels should be higher. In regions with well-distributed rainfall during the growing season they may need to be slightly lower.

Since a water table averaging 36 inches deep takes 1 to 2 inches more rain to saturate the soil than one averaging 24 inches, many farmers prefer to maintain low water tables for storage as a safety measure rather than provide additional runoff capacity. A water table held at the higher level of 24 inches, however, will cut oxidation losses over one held at the lower 36-inch level to the extent that the productive life of the soil will be increased an average of 50 to 80 percent. The exact rate of increase depends on climatic conditions and soil type. Thus in the long run it will prove cheaper to provide adequate runoff facilities in place of depending on storage capacity of the soil.

As a general rule, the higher the water level can be safely held without root damage, and the more consistently it can be maintained at the same depth after plant germination and initial root development, the better the crop yields will be. Further, the most practical way of holding the loss of peat and muck soils to a minimum is by controlled drainage whereby the water level is held as high as crop and field requirements will permit.

Proper water control presumes a water supply to be available to make up any deficit during dry periods. Water for such a system may come in part from the field ground water and seepage. Where this is insufficient to keep the water table to the desired level, water must be supplied from outside the field by gravity or by pumping into the system. In some places the needed water may be obtained from wells or from storage ponds.

Normal crop water consumption by evapotranspiration will amount to from one-eighth to one-fourth inch a day, the rate depending primarily upon solar energy on the leaf surfaces. That amounts to about 3,500 to 7,000 gallons of water used on each acre a day. That amount should therefore be available for irrigation in addition to seepage or other losses from the field.

As soon as drainage requirements are met, a system of control dams or gates should be provided to regulate water stages. The structures should have adjustable spillway openings that can be operated to raise or lower the water level in the drainage system in accord with needs of the day and should be capable of passing the designed runoff flow without undue restriction during floods.

Surface flooding is desirable for halting subsidence in organic soils and also for combatting certain diseases and weeds. The structure should therefore be capable of holding the water table near the surface when the land is not in use. The control dams should be spaced to hold differential water tables not exceeding about 1 foot, the number being determined by the slope of the field.

Dams to control ditch levels may be of timber, steel piling, masonry, or concrete. Metal culverts or other types with attached risers often are used in places where it is advantageous to have a road crossing combined with a control. The simplest control dams use the stop-log arrangement, which consists of grooved piers with wooden timbers spanning the space between them. The timbers are placed or removed individually, either with hooks, by hand, or by use of small, manually operated hoists. Small, portable, panel-type pumps that fit into the grooved openings are valuable for field irrigation where gravity flow is unavailable. Culvert pipes equipped with sliding headgates may be used, but trash accumulates worse behind any underflow type of spillway. On the larger developments, where high head-control structures are required, radial gates, roller gates, or sliding gates operated mechanically or manually are preferred.

Water checks in tile lines can be of simple construction. They consist of a wooden, steel, or concrete catch basin that has vertical grooves in the center section. When the boards are in place, impounded water backs up until it reaches the gate-board level and overflows into the tile below. Even simpler are galvanized iron plates, which can be slid into the joints between the tile and withdrawn as desired. The use of the catch basins, with control weirs, is to be preferred, as they need less attention and provide automatic relief in case of flash rainfall when the crest level is reached.

From a practical standpoint it is impossible to hold a precisely uniform level under the whole field, because the surface of the water table will form a series of undulations between the field drains whenever there is an appreciable movement of the soil water toward or away from the drains. Under drainage, the undulations will trough at the drains and crest about midway between them, while under subirriga-

tion the positions will be reversed. The shape and gradient of the profile of the water table will vary with the effective permeability of the soil, being abrupt with low permeable soils and subdued with highly permeable soils. As the flow of ground water under gravitational influence diminishes, the slope of the water table becomes flatter.

In order to observe the actual ground-water levels in the field between the drains, it is suggested that shallow observation wells, properly cased, be sunk at strategic locations in the field. They are helpful in determining the water levels needed in the ditches to effect proper ground water levels under the crop.

Soil moisture usually is supplied through subirrigation by simply backing the water up in the ditches or tiles and allowing it to seep laterally through the soil. In soils where the water movement is very slow, however, this method may not be feasible, and overhead irrigation will be preferable. Also, if the water supply is limited or the land surface is too rough for subirrigation, overhead sprinklers are favored. They are used also during germination and for transplanting such crops as celery.

PUMPS ARE REQUIRED often for drainage of peat and muck lands and for irrigation during dry periods. Lifts are usually low in pumped districts on organic soils, and low-lift, high-volume pumps commonly are used. The design and construction of pumping stations for peat and muck lands follow the same principles governing pumping plants for other drainage. Allowance must be made for subsidence, however, and the intake must be low enough to provide for lowering the surface during the life of the installation.

Permanent installations are provided with permanent foundations and protected from the weather by housing. Costs of the farm pumping plants range generally from 150 to 300 dollars per cubic foot per second for the complete installation.

Crops on organic soils are damaged by cold oftener than are similar crops grown on nearby mineral soils. Organic soils occur in depressions, where the heavy, cooler air settles. The thermal characteristics of organic soils differ markedly from those of mineral soils. Organic soils, in comparison with mineral soils, have a high coefficient of absorption and emission of radiant energy; a high heat capacity, which increases with moisture content; and a low coefficient of heat conductivity, which can be increased by compaction or added moisture.

During daylight, the dark organic soils absorb more radiant energy than the light-colored mineral soils. Its high heat capacity demands more heat to raise soil temperatures than do the mineral soils, but this same capacity is conducive to more storage of energy at equal temperatures than mineral soils. This stored heat is released on clear nights into outer space as radiant energy, which is not effective in warming the air because of the poor heat-absorptive quality of clear air.

Under the laws of heat exchange, the surface soil must receive and absorb as much energy as it is radiating. Since the heat conductivity of the dry organic soil is low, the heat is robbed from the air next to the surface, and the temperature drops. If there is no wind movement to mix the air, the temperature near the ground surface drops quickly. An upward temperature gradient, or temperature inversion, thus is established.

If clouds intervene to absorb and reflect the nocturnal radiation or if a breeze mixes the air to prevent the layer of air near the ground from excessive cooling, frost damage is less apt to occur.

Heat transmission is more rapid in moist soils than in dry. A dry surface layer on peat or muck is a poor conductor, and it retards the transfer of heat from the subsoil to the surface to replace radiant losses. On the other hand, a rolled, compacted, moist soil augments the exchange and consequently reduces the chances of crop

damage on the cool, clear, calm nights.

Surface flooding of the area or even raising the water level in the field is an effective method of protecting it against frost. The practice is safest in places where the water-control system can be operated to obtain rapid change in ground-water levels. When it is doubtful whether the crops can tolerate the necessary higher water levels, sprinkler irrigation is safer and as satisfactory.

The presence of a body of water, such as a lake, cushions sudden changes in temperature and reduces the risk of frost damage. Muck areas close to the Great Lakes are especially favored. The lands near Lake Okeechobee in Florida are similarly protected against cold spells and are highly prized for growing truck crops.

Air drainage and wind movement are important considerations in frost prevention, and the value of windbreaks to prevent soil blowing and crop damage should be balanced against their hindrance to air movement and mixing in places where tender crops are grown. Helicopters and wind machines have been used with varying degrees of success to stir the air over fields.

Organic soils that have been tilled long enough to develop a mucky surface condition are better heat conductors than raw peats and therefore are less frosty and safer for tender crops than the newly developed lands. A surface covering of sand, such as is used in cranberry bogs, also reduces danger of frost damage.

Frosts on muck can be combatted by the selection of crops that are least susceptible to damage. H. C. Thompson, of Cornell University, grouped vegetables into three classes with respect to cold resistance: Hardy (which will stand hard frosts), such as kale, spinach, turnip, mustard, onion, peas, and cabbage; half-hardy (those that will withstand light frost) such as beets, carrots, parsnips, celery, and chard; tender (those that will not withstand any frost), including beans, sweet corn, lima beans, squash, pumpkins, melons, cucumbers, okra, tomato plants, eggplant, and pepper plants.

THE MANAGEMENT of organic soils differs from the management of mineral soils in several respects. Peat is porous and open and ordinarily does not require plowing every year. In fact, rolling and packing is often important in the management of such land. Compaction allows the roots to come in closer contact with the soil. It facilitates the rise of water from below, which benefits germination, lowers frost hazards, and tends to reduce soil blowing during dry weather. Generally, cultivation should be more shallow than for mineral soils, especially after root development begins.

Commercial fertilizers ordinarily are more desirable than manure. Nitrogen may be needed on raw peats, on the more acid peats, or on poorly drained areas, but less often on good, thoroughly decomposed organic soils, which especially require potassium and phosphorus and generally need such microelements as copper, manganese, zinc, and boron. Common salt benefits some crops. The amount, kind, rate, and time of fertilization depend on the crop to be grown, the climate, the chemical and physical nature of the peat or muck, and its drainage, previous fertilization, and length of time under cultivation.

On the basis of soil tests and degree of drainage, special recommendations have been prepared by many of the State agricultural experiment stations on fertilizer grades, placement, rates of application, and the addition of microelements.

With proper control and management of water, many crops can be grown on organic soils. In Florida, vegetable crops, including beans, sweet corn, pepper, cabbage, and celery, are grown for the winter market. Sugarcane and pasture grasses, especially St. Augustine grass, do very well. Ramie, a fiber, thrives on these soils. In California, corn, potatoes, onions,

sugar beets, asparagus, celery, and other special vegetable and field crops are grown on the organic soils. In Pacific Northwest, peat and muck lands produce forage and the vegetable crops that are suited to climatic conditions and market demand. Cranberries are grown in Massachusetts, Wisconsin, New Jersey, Washington, and Oregon. The plant grows wild only on acid peat or muck bogs—a good indication of the soil requirements of the plant. Blueberries do well under similar conditions.

In the organic soils of Sanpete County, Utah, the only practical known method of securing a moisture supply is by flooding the soil during late winter and early spring. The Utah Agricultural Experiment Station recommends a crop rotation on peat of barley or oats, 1 year; sweetclover, 1 year; or barley or oats, alternating with a clean, firm, summer fallow. On mucks a longer rotation of crops, including canning peas and potatoes, is suggested. The commercial production of celery and cabbage on the mucks there appears to depend on development of an adequate water supply for supplemental irrigation.

In the Great Lakes States, peat and muck soils are used in several systems of crop production, depending on size and quality of the deposit, location in relation to markets and climate, drainage facilities, and the experience and preference of the operators.

The University of Wisconsin Extension Service lists these uses for the organic soils: Supplementary forage production on farms where major cropping is on upland areas; both forage and cash crops on farms where no upland is available (on these farms sweet corn, cabbage, grass seeds, onions, mint, root crops, and some leafy vegetables are raised if frosts are not too much of a hazard, a ready market exists, and labor and equipment is available); special crop production if crops of high gross income, which require good drainage and intensive cultural and land management practices, can be grown. Income from such crops is subject to considerable fluctuation, and diversification of crops is indicated for the average farmer.

In New York and New Jersey, good agricultural organic soils are desirable for the production of truck and other special crops, because they are close to city markets. The more acid peats are used for cranberries or mined for use in lawn improvement and other horticultural purposes. In Maine the present use of the peats is for litter or pulp production.

THE RECLAMATION of the Everglades of Florida illustrates water-control methods that have been employed in the reclamation of large bodies of organic soils.

The Florida Everglades contains more than 3,100 square miles of peat and muck soils. The soils were formed in a sedimentary trough of limestone about 100 miles long and 40 miles wide, southward from Lake Okeechobee to the sea. Arms of the Everglades also extend partly around the eastern and western shores of the lake. The Everglades is bordered on the east by the narrow Atlantic coastal ridge, which reaches an elevation of about 15 feet, and on the west by a low, anticlinal arch, which rises to an elevation of about 25 feet and embraces the areas known as the Big Cypress Swamp and the Devil's Garden.

In past geologic times, Lake Okeechobee, an almost circular fresh water lake of about 725 square miles, received the water carried by the Kissimmee River and other tributary streams, which drain a watershed of about 4,000 square miles. The lake, having no definite outlet, overflowed its south and eastern rim when it reached a stage about 20 feet above sea level. The overflow, together with an annual rainfall of more than 60 inches, moved slowly through the thick vegetation over the almost level plain of peat and muck to escape eastward through a few small rivers transecting the east coast barrier ridge or to pass even-

tually to the sea through dense mangrove forests at the tip of the peninsula.

Silt, clays, and organic colloids were carried in suspension and deposited during intermittent overflows near the shore of the lake to intermix with the remnants of plants to form mucks. Because those soils contained sufficient amounts of the microelements that the peats lacked and were relatively free from frost, they became highly prized cropland when they were drained. In the ancient floodways along the eastern and western margins of the swamp, submersed succulent aquatics grew and later formed a very light sedimentary peat, which was found to be unsuited for reclamation and is used for water storage and as a fish and wildlife refuge. Most of the Everglades soils, however, were derived from sawgrass and related marsh plants, which formed a light, felty, brown, fibrous, low-moor peat with a low ash content. When drained, fertilized, and augmented by minor elements, it breaks down into an excellent field soil under tillage. This type of soil today makes up the greater part of the productive agricultural lands of the 'Glades.

The total area of the Everglades mantled by peats and mucks is approximately 2 million acres. Because of shallow depths or poor soil type, something less than half of that acreage is deemed suited for agricultural development.

The original condition of the Everglades has been greatly altered by drainage works, first by State and local interests and later by the Federal Government. Premature attempts at drainage began about 1880. Intensive drainage operations began in 1906 after the Everglades Drainage District, including approximately 4.5 million acres, was created by the State legislature. The early plan was to extend the several short, coastal rivers through the marsh to tap Lake Okeechobee, but that soon was found to be inadequate to control high lake stages. The lake was impounded by muck dikes to block escape of lake water into the Everglades, and additional outlets were constructed directly to the sea. The original canal system was left to serve the peat and muck lands. Even then the system proved inadequate; lands were overdrained during the dry season and underdrained during the rainy season. In 1926 and 1928 the muck dikes around Lake Okeechobee were swept away by hurricane-driven lake water. The resultant overflow and flood caused great property damage and loss of life. Control of the lake stages to provide for flood protection and navigation was undertaken by the Federal Government. The muck dikes were replaced by substantial rock levees. Enlarged outlet canals, provided with hurricane-proof control gates, were constructed. Those measures have proved to be effective against overflow.

Meanwhile it was found that farming in the Everglades could be successful only if the fields were surrounded by dikes to prevent overflow by high water from the canals or surrounding lands. Reversible pumps were also found necessary to pump water from the fields into canals in wet seasons and water from the canals into the fields during the dry season. For local water control, subdrainage districts were organized. The districts have constructed ditches, dikes, and pumping plants, which afford varying degrees of protection for about 150,000 acres. Individual landowners outside subdrainage districts have provided water-control facilities on some 40,000 acres.

Investigations by the Department of Agriculture and other agencies published in 1948 revealed that improper water control had resulted in overdrainage during dry periods, with excessive loss of soil from burning and oxidation. The average loss of depth was found to average about 1.25 inches each year. The better soils in the northern Everglades lost 40 percent of their original volume during 40 years of drainage. Salt water from the ocean also found its way inland under the

coastal cities during periods of low rainfall.

Heavy rainfall and hurricane winds in 1947 caused inundation of the entire Everglades area, even though overflow from Lake Okeechobee was blocked. The flood damaged nearly 50 million dollars worth of property and revealed that works of the Everglades Drainage District were insufficient for flood control.

In 1949 a comprehensive plan of flood control and water conservation for central and southern Florida, including the Everglades, was drafted and authorized by the Congress and the Florida Legislature as a cooperative Federal, State, and local program. Plans called for substantial rock levees as an additional protection against overflow, enlarged arterial canals designed to transport water to giant pumping stations capable of removing 0.75 inch of runoff in 24 hours, and pumping of wet-weather runoff from agricultural lands into Lake Okeechobee and into leveed areas of the Everglades set aside for water conservation, where it will be stored for irrigation use in dry weather.

Pumping installations in the Everglades range in size from small portable field pumps, capable of moving 500 gallons a minute, to giant plants for use in the operation of the Central and Southern Florida flood-control program. One such plant on the West Palm Beach Canal serves an agricultural area of 230 square miles. It has a designed capacity of 4,800 cubic feet a second at a lift of 11 feet, with a pump efficiency of 75 percent. The plant contains 6 individual pumps of 800 cubic feet capacity and powered by diesels of 1,600 horsepower. The total construction cost of the plant is estimated at around 3.5 million dollars.

Most of the subdrainage district pumping units use screw-type pumps of capacities of 30,000 to 60,000 gallons per minute and are powered by diesel engines. The units are so arranged that water may be pumped into the drainage system when needed. Records kept on four large pumping districts from 1933 to 1938 showed the average static lifts varied from 3.5 to 4.4 feet. The mean depth of water pumped off the districts varied from 2.3 feet to 4.4 feet annually. The total annual cost of pumping, including fixed charges, which amounted to about two-thirds of the total cost, varied from 1.45 dollars to 2.57 dollars an acre.

In the Everglades, where the majority of individual farm pumps have capacities of 5,000 to 30,000 gallons per minute, requirements for pumping installations are typical of those for most peat and muck lands. In meeting those requirements, two types of pumps are most commonly used. In places where portability and reversal of flow are desirable features, a panel-mounted, modified centrifugal pump has found favor. It has a vertical shaft and double intake openings with peripheral flow produced by an impeller within a volute casing. A flap valve prevents backflow. Operation tests showed the pool-to-pool efficiency of this pump varied from 30 to 40 percent at lifts of 3 to 9 feet and at different speeds, with little variation in efficiency because of changes in speed or lift.

For permanent installation, a popular type is the axial flow, 3-bladed, propeller pump. It is usually mounted within a double-decked chamber, with intake from the lower chamber. A floating bell, activated by the upward flow, settles to seal off backflow when pumping ceases. Direction of flow is controlled by the manipulation of stoplogs within the grooves of the upper and lower chambers. A similar pump, with the same impeller and general design characteristics, is enclosed in a tubular casing for portability. It is popular for semipermanent installation where pumping over a levee is desirable. The chamber-mounted type varies in efficiency from 45 to 60 percent.

Internal combustion engines are in universal use in places where pumps are used primarily for drainage. Electric motors for pumping in the Everglades are limited to use for irrigation,

where power failure during storms is not detrimental. In other districts not visited by hurricanes the use of electric power may be desirable because of the facility with which water stages can be controlled.

The use of open ditches, supplemented by mole drains, is accepted practice in the Everglades. Here, the ditch systems have laterals a half-mile apart on section and half-section land lines. The farm ditches are dug at right angles to the laterals and are commonly spaced 660 or 1,320 feet apart. Thus the farm is divided into fields of 40 or 80 acres and drainage units of 20 to 40 acres. The closer spacing is needed for truck crops and the wider spacing for sugarcane and pasture. Mole drains 12 to 15 feet apart are pulled into the farm ditches at right angles to them.

The laterals are about 15 feet wide and 4 to 6 feet deep. The farm ditches have nearly the same depth but are narrower. The fibrous peat has a predominantly columnar cleavage and the ditchbanks will stand on steep slopes. Some ditches are dug with almost vertical sides, and side slopes are seldom flatter than 0.5 to 1.

As the land is practically level, a fall of 3 inches to the mile is usually used in computing ditch sizes. A coefficient of roughness "n" of 0.035 for the laterals and 0.040 for the smaller farm ditches is used with the Manning formula. Those fairly high values are necessary because of the rapid growth of subtropical aquatic plants, such as water hyacinths, paragrass, and submersed mosses, which reduce the flow capacity.

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The Disposal of Seepage and Waste Water

William W. Donnan and George B. Bradshaw

An estimated 8 million acres of land in the West need drainage. An additional 8 million acres would benefit from better drainage.

A serious economic problem hangs thereby. Most irrigated areas are put into production only after large sums are spent for developing a water supply, conveying it to farms, and leveling land. If more money must go into drainage and reclamation, where is the profit?

It seems a paradox that drainage problems should occur on lands that we consider arid. What causes them?

Perhaps the foremost cause is excessive use of water. Water that is plentiful and cheap often is used in excess. The result is a general waterlogged condition. Wild flooding, continuous irrigation, lack of waste outlets, and excessively long irrigation runs tend to promote waterlogging.

A second cause is seepage from canals, laterals, and ditches. Of the 135,000 miles or more of irrigation canals and laterals in the 17 Western States, only 6 to 8 percent are lined. The rest are untreated earth channels. They are the cheapest to build, but they permit seepage losses that may amount to 70 percent of the water diverted into them. The seepage enters underground strata at elevations higher than those of the irrigated lands and often—as in South Platte Valley in Colorado, the North Platte Valley in Nebraska, and the Big Horn Basin in Wyoming—becomes a direct source of waterlogging of lower lying areas.

A third cause is the inherent stratification of irrigated soils in the West. Many irrigation developments were feasible because they included a plan for irrigating the broad, flat, alluvial

plains, lacustrine valleys, and ancestral lake basins. Because of the way the soil materials are deposed in those areas, their internal natural drainage often is poor. Sand layers are overlain or underlain by relatively impervious strata of clays or other slowly permeable soils, which, when irrigation water is applied, impede the percolation of the excess. Thus perched water tables—as in the Imperial Valley and the San Joaquin Valley of California—are formed.

A fourth cause is artesian pressure from underground sources. Wells drilled downward to penetrate underground aquifers often produce flowing wells, which may or may not be utilized fully for irrigation. Entire valleys have become waterlogged because of the uncontrolled flow of artesian wells. Examples are Cache Valley and Weber Basin in Utah and the Payette Valley in Idaho.

Other causes of drainage problems in irrigated areas stem from the mineral elements in the irrigation water, mineral elements in the virgin soil, the topographic features of the area, the nature of the crops, and combinations of the causes.

No shortcut method can solve all drainage problems. Some problems are simple. Most of them, however, require an investigation of the natural elements in the valleys and their complex of soils, water, crops, and irrigation practice. Holes must be bored, observation wells must be installed, and readings taken.

The main aspects to be considered in any investigation of drainage are topography; soils; salinity, alkalinity, or acidity of the waterlogged areas; and the tables, sources, and quality of the ground water. Some questions need to be answered: Is there an outlet for drainage water? Can the excess water be removed from the soils? Does the water come from rainfall, irrigation, seepage, or artesian pressure? How much water must be drained? What type of drainage system will give the best results?

The first step is to review data pertaining to the area—contour maps, which might eliminate the need for making a topographic survey; aerial photographs that reveal the existence of seep areas, saline-alkaline spots, the source of water, and perhaps (by the amount of plant growth over them) the presence of underground clay barriers and sand pockets; old engineering reports originally made with possible expansion or reclamation in view; geological papers, water supply bulletins, studies at experiment stations, soil surveys, and State engineering publications.

The historic aspects of the problem might well be analyzed. Perhaps the area always has been poorly drained. Perhaps somebody tried in vain to change a quirk of Nature. The problem may have developed with the installation of a canal, dam, or reservoir. It may be the result of a change in crop production or the drilling or abandonment of wells. It may be connected with the expansion of nearby irrigated areas. Gradual encroachment over a period of years might be an indication of poor irrigation practices.

A field reconnaissance should be made over the problem area, preferably in the company of a person familiar with the land. The inspection should be thorough enough to acquaint the investigator with the number and general location of natural waterways; the location and condition of possible outlets for any proposed drainage; the location and general characteristics of any canals, laterals, wells, ponds, springs, reservoirs, or other water sources; location and general characteristics of nearby drains; general characteristics of the irrigation practices; leveling, grades, mode of water application, and efficiency; location of topographic features like dunes, benches, pockets, and outcrops; estimate of the present water level and any information available on its fluctuations; present cropping practices, condition of crops, and any change from previous years.

Actually the reconnaissance can be made quickly. They should form the basis of all further investigations.

THE SECOND STEP is a ground-surface investigation, or topographic survey. The survey is made to determine the surface configuration of any proposed drainage area. It establishes the surface slopes and reveals the potential drainage outlets. It reveals the degree of land preparation in the irrigated areas and points up the fact that sometimes poor leveling rather than poor drainage causes crop failure. The survey also should indicate the direction of drains, the type of drain system (surface, tile, or pump) that could be used, and, to a degree, some of the economic factors involved. Thus if the natural grades, outlets, and surface configurations are favorable, the drainage system will be less costly than otherwise.

The field surveys generally should provide all the physical measurements necessary to map the surface configuration. The map becomes the base from which all measurements, vertical and horizontal, are made.

Data from the topographic survey should be analyzed. Surface configuration may reveal the path of underground flow of excess seepage or the concentration point of this movement. Breaks in slope, benches, alluvial fans, old creek channels, canals, or natural drainageways could be important to the drainage problem. Locations of springs, seeps, abandoned wells, or diversion points might be the key to the solution.

THE THIRD STEP is to make a soil survey, which is highly important in a drainage investigation. The survey determines the location, extent, and physical characteristics of the underlying layers of soil materials. Points to be considered in the soil are: What types of soils are present? How thick are the various strata? Are the strata continuous and interconnected? What is their vertical position with respect to the ground surface and to each other? What is the hydraulic conductivity of each stratum and the average hydraulic conductivity of the waterlogged profile?

The equipment needed in making a soil survey depends on the information required. Of the many types of augers used to make soil borings, perhaps the most common type is the posthole auger. The orchard auger, a modification of it, uses a 4-inch, cylinder-shafted bit 10 inches long, with two cutting leaves on the bottom end. It was developed for sandy soils. Many different types of screw augers are used for soil boring. The ordinary 5-foot soil auger, with a 1-inch screw bit, is useful for making shallow investigations, but it is not long enough for surveys of subsurface drainage.

Several power augers are available. One is a portable digger, which fits into the bed of a pickup truck. It has a 4-cycle, 3-horsepower gasoline engine mounted directly over the drive shaft. It will drill to a depth of 6 feet.

When a reconnaissance is required of the sequence of sands and clays to depths of 20 to 100 feet, perhaps the best type of device to use is a jetting rig. Water is pumped under pressure into a tube one-fourth inch to 1 inch in diameter. As the tube is forced into the ground, the feel of the tube as it moves downward, and the eroded materials that bubble out around the outside of the tube, give an indication of whether the tube is in sand or clay.

The reconnaissance below 20 feet in the substratum sometimes is important, especially if deeper artesian pressures are believed to be a factor. The jetting technique has some limitations. Often it is difficult in caliche or other hardpans. When extremely coarse gravels are encountered, aqua-gel or drillers' mud may be used with the jetting water to assist in penetrating the strata.

If one needs soil samples for analysis of physical and hydraulic characteristics, the auger type of tool and the jetting technique are not applicable. Several inexpensive types of coring

tubes can be used to obtain in-place cores.

The depth of borings is important. In the drainage of irrigated lands, information is needed on the character and the extent of the drainable strata to depths of at least 10 feet and frequently much deeper. Because the ground water in irrigated areas often contains harmful amounts of salt, water tables must be lowered to depths of 4 to 5 feet so that the roots of growing plants are not adversely affected. The water table must be kept at low elevation in order to control the upward movement of salt. If tile lines or open drains are used to drain the land, they will be installed at depths of 5.5 to 8 feet in the case of tile lines and 6 to 12 feet in the case of open drains.

Water moving through the soil to a point of release, such as a tile line or open drain, follows a curved path or streamline of flow. If the soils are homogenous, the flow pattern may go down below the drain device and back up into the drain. If the soil is stratified, the fine-textured soils restrict the streamline flow. The restricting layers of soil therefore might dictate the spacing requirements and the best depth for tile lines.

Thus if the investigator does not know the character of the soil material below 5 feet, he may design a tile line that would be placed in the unknown clay layer at 6 feet or even below a clay layer. Knowledge of the soil strata is therefore essential to depths of 8 to 15 feet, for tile and open drains; 15 to 25 feet, for sumps and shallow wells; and to the proposed depth of the wells, for drainage by means of pump wells.

A log should be made of each hole bored, preferably at the time the boring is being done. At the same time the hole should be located on the map of the area so that a delineation can be made showing boundaries of different types of drainable or undrainable soils.

As the hole is being bored, notes should be made on the log sheet of any pertinent information, such as the depth to the water table; relative moisture content of various strata; staining or discoloration of the soil particles; and the presence of roots, minerals, and other characteristics. If core tubes are used, the soil structure, minute stratification, and presence of lenticules (or sand-filled cracks) in clays should be noted. Characteristics to look for in sand strata are minute layers of silts or clays, which tend to slow up the movement of water through them. Characteristics to look for in clay strata are sand-filled cracks, which make an otherwise almost impermeable barrier layer into a slowly permeable stratum. By watching for and recording these individual characteristics it is possible to classify and segregate otherwise seemingly similar strata.

Various laboratory analyses can be made of soils to determine their drainability—that is, their texture, structure, grain size, pore space, dispersion, aggregation, swelling, and mineral content, all of which influence ability to transmit or release water.

An estimate of the hydraulic conductivity of the strata underlying the soil surface is necessary in the development of sound techniques. The hydraulic conductivity of any stratum or group of strata may be determined by field measurements (direct field measurement of the conductivity of the entire soil profile with a pumped well or the auger hole method, and measurements of strata with a small tube or piezometer); by laboratory measurements, utilizing a permeameter device; and by indirect measurements, utilizing texture, mechanical analysis, the percentage of silt plus clay, percentage of pore space, and plastic limit.

The field measurements, perhaps the most accurate, require special sites and take more time. The laboratory measurements are rather accurate when inplace samples are used, but they also take a great deal of time and special equipment. The indirect measurements are good only when basic data are sufficient to establish the index.

A survey should be made to deter-

mine the nature and extent of concentration of harmful mineral elements in the soil profile. The degree of salinity, alkalinity, or acidity of the waterlogged soils affects the overall reclamation cost after drainage. Highly saline soils may require long periods of ponding of water on the soil surface to leach out the excess accumulation of harmful elements. Highly acid soils may require heavy applications of lime. Equipment to test salinity and alkali may be simple color indicators or resistance bridges and complete laboratory ionic analysis. Visual inspections that utilize plant indicators, salt deposits, and color of indicators can be used for preliminary reconnaissance. Soil samples should be sent to a laboratory and be subject to further analysis before recommendations are made for reclamation.

The survey of the water table is an important part of any drainage investigation. Observation wells are installed to determine the position of the water table at different points in the problem area and in the various soil strata. Observation wells also are used to determine the extent and degree of severity of the problem. Poor crop production, marsh areas, or alkali spots usually are evidence of waterlogging. The observation well, however, gives positive data on the position and fluctuation of the water table.

Plotting water-table hydrographs in sequence with precipitation, irrigation, runoff, pumping, or other hydrologic phenomena may give a clue as to the cause of the rise or fall of the water table. In many places some records of water levels, depth to water table, maps, or other data are usually available.

The type, location, and number of additional observation wells are determined by the type of information needed. The most common type is an ordinary well—an open hole bored with a soil or posthole auger or a well drilled with a commercial rig. A well of this type, if it is to be used for any length of time, should have a casing of sheet-metal pipe, stovepipe, drain tile, or standard commercial types of well casing.

A grid of wells is effective for a valleywide investigation. A grid oriented to the strata survey grid facilitates correlation with soils data.

Observation wells are generally installed by placing the pipe in an auger hole. A hole is dug with the auger to the desired depth. Pipe of any size, one-fourth inch to 6 inches, can be used as a casing. Pipe open only at the ends should be backfilled properly to insure that it is a true well. The proper way to backfill the well is to place the open pipe on a small amount of gravel on the bottom of the hole. Gravel is then backfilled around the pipe to a point above the ground water table. The native material can then be used to fill the rest of the hole to the ground surface. The well pipe projects 16 inches or so above the surface.

Open holes made by soil surveying can also be used as observation wells.

A ground-water piezometer is a useful tool in a drainage investigation of any type. It is a small-diameter pipe driven into the soil so that there is no leakage down the outside of the pipe; water can enter the pipe only from the bottom.

An ordinary well usually indicates the depth of water, or hydrostatic pressure, of the entire underground soil profile to the depth of the well; water seeps into an open uncased well at all points and fills the hole to whatever height the strongest hydrostatic pressure will produce. The piezometer is designed to indicate the hydrostatic pressure of the underground water only at the bottom end of the device. Water can enter the piezometer only at the bottom and is sealed off on the outside throughout the length of the pipe.

Because underground water moves from a point of high hydrostatic pressure to one of low hydrostatic pressure, the movement of water can be charted if the hydrostatic pressures are measured. Sets of piezometers spaced at intervals depict the hydrostatic pressure

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of an entire profile and help the investigator determine seepage movement. Jetting has been used to install piezometers and wells to a depth of 100 feet or more. Jetting permits a much greater depth than driving.

IF THE SOURCE of excess water is precipitation, the remedy might be better surface drainage. If it is canal seepage, it would call for an interception drain. An artesian pressure would suggest relief wells.

In some areas the source of water is obvious. In many western valleys, however, the sources of water are many. The source can be found by combining the information mentioned on geology, topography, soil strata, nature and concentration of mineral elements, and water table until a pattern develops that points to the source.

Records of the monthly distribution and the long-term trend of precipitation should be analyzed. The distribution of precipitation should be related to the fluctuations in the water table. If they coincide, precipitation may be dominant as a water source. If not, the precipitation probably has little effect on the water table.

Longtime records of precipitation should be related to longtime hydrographs of water levels, if possible, to determine whether wet spells are followed by rising water tables, and vice versa. Deep seepage to artesian or other aquifers is slow but often is manifested by a rise in water levels, perhaps years after the peak of a wet period. In some localities rainfall is less significant than the previous periods of snowmelt. Precipitation affects artesian wells, deep static wells, and shallow piezometer wells differently. The response of the water surface in the wells would indicate the degree, mode, and duration of influence of precipitation on the water table.

DRAINAGE PROBLEMS in irrigated areas often are traceable to irrigation practices.

In order to determine what effect irrigation practices have on the water table the following should be considered: The effect on the water table of the individual irrigations; water-table fluctuations throughout the irrigation season; and changes in water-table elevation over a period of years after irrigation is begun.

Seepage is a major source of water in places where drainage is a problem. Manmade seepage usually stems from irrigation development works such as canals, reservoirs, or similar structures. Comparisons of fluctuations in ground water levels and fluctuations in water levels in canals or reservoirs will indicate whether the structures are leaking. Subsurface seepage often is shown by the growth of tules, willows, or other water-loving plants.

An underground aquifer under hydrostatic pressure may be a source of water. Artesian pressures are caused by confining impermeable layers which impede free vertical flow of water. A well drilled through them forces the water to the surface as a flowing artesian well. It is important to determine which aquifer is responsible for the artesian pressure. It then might be possible to trace the continuity of the stratum to its source.

Examination of well logs often provide the clue as to which aquifer is under pressure. Other clues would be the measurement of the pressure differential in wells of different depths; the period of peak pressure in different wells; and the quality of water in various wells. It is not uncommon in artesian pressure areas, for example, that several aquifer zones are separated by layers of shale or heavy clay. Measurement of the pressure in wells that tap different confined strata will show the relative significance of each.

The quality of water in various artesian wells is probably the most valid clue to the source point. A relatively pure water, free of saline elements, suggests the source to be runoff from precipitation or some deep-level recharge from surrounding watershed areas. Water high in calcium carbon-

ate suggests a limestone aquifer. Some contaminating saline elements are traceable for many miles. Other minerals, like boron, often are used to classify and identify artesian zones and sources of pressure.

Wells have been drilled for both domestic and irrigation use in many western valleys. Wells 50 years old are not uncommon in many irrigated areas. Old wells, especially old artesian wells, often are the source of seepage water from one stratum to another. Leakage between strata, common in many old wells, causes a loss of water in the well and may cause waterlogging of soil nearby.

Natural springs and seeps may be the cause of the drainage problem. One common type originates at the base of steep slopes where a break in topography occurs, generally coincident with an abrupt change in the character of the soil.

They usually occur along the periphery of the valley and are characterized by perennial flow and fresh cold water.

Another type is caused by the fracture or displacement of confining clay or rock layers above an artesian aquifer. The water in those artesian zones forces its way to the surface as a spring or seep. Thus a line of springs may delineate a fault line. Such springs are often thermal and may contain excessive amounts of mineralized elements. An old saying is that the depth of source of water feeding a spring can be estimated by the temperature of the water—the deeper the source, the warmer the water. It is true that the deep-seated fault springs usually are warm, whereas the shallow springs, originating as bedrock outcrop seepage, are cold. Springs and seeps are important in that they indicate natural characteristics of the problem. They indicate where the natural outcrops of water occur, thus pinpointing known sources.

THE INHERENT QUALITY of the ground water of the area to be drained is important. Tests should be made to determine the character and amount of mineral elements in the soil and water.

A drainage problem usually falls into one of three types: Drainage of "sweet" water from the problem area; drainage of saline or alkaline water; and drainage of saline or alkaline water and removal by leaching of excess concentrations of mineral elements in the soil.

Each type poses a different set of conditions. It is important to know the kind of ground water before a solution to the problem can be developed. For example: If the soil water is not saline, the solution to the drainage problem becomes a matter of lowering the water table to a point where it will not interfere with the root zone of the plants. In addition, some latitude exists in the permissible fluctuation of the water table. If the soil water is saline or alkaline, the water table must be lowered to a point well below the root zone and kept down, so that evaporation and transpiration will not concentrate the elements in the root zone. If harmful mineral elements must be leached out, the drainage problem becomes harder and necessitates a provision for draining excess water out of the soil and for removing the water that was used to leach the salts. The leaching of plant food often becomes a problem where drainage systems are proposed.

Thus it is that topography, soils, concentration of mineral elements, water table, water source, and water quality become the key to investigations of drainage in irrigated regions.

The topographic survey may reveal a lack of natural outlets for drainage water or that the terrain is unsuited for the construction of open drains except at excessive cost. The basin type of topography lends itself well to pumping for drainage. Disregarding other factors, flat slopes lend themselves well to tiling on a grid system. Swales and benches suggest the use of interceptor lines. Pockets requiring drainage are usually best drained by sumps. The extent and effectiveness of existing canal systems often suggest the best location for open drains.

The soils influence the choice of a drainage system in many ways. The sequence of permeable and impermeable strata in the area and the ability of the separate layers to transmit water largely determine both the type of system that should be installed and its design. Open drains at 1-mile intervals may be adequate for draining areas of extremely porous subsoils, but a relatively heavy soil might require tile lines spaced not more than 100 feet apart. Lack of drainable strata in the 4- to 8-foot zone may make drainage by tile lines unfeasible.

The nature and extent of concentration of harmful mineral elements influence the choice and design of the drainage system. Areas requiring prolonged leaching call for the installation of tile drains.

The height, movement, and cyclic trends of the water table determine or affect the choice of drainage measures. For example, artesian pressure areas are extremely difficult to drain with tile lines, and relief pumps usually are necessary to relieve the pressure from below. Streamlines of flow indicate the points where seepage can be intercepted to advantage.

The survey of water sources indicates the amount of water for which drainage must be provided and the nature of its source. If rainfall is a factor in the drainage problem, open drains usually are essential for removing excess surface flow. In dry western places in which rainfall is not excessive, pumping may be the solution.

Determinations of water quality are important in areas that lack adequate water supplies. If drainage water is of good quality, for example, plans can be made to reuse it for irrigation. If a drainage system can be made to produce usable water at the points where it is needed, the cost of drainage can be greatly reduced or almost completely written off.

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Drainage in Forestry Management in the South

E. A. Schlaudt

The drainage of pine forests is a new practice in the Southeast. Only a small acreage was known to be drained or considered for draining in 1950, but since then plans have been made or completed for draining about 750,000 acres of wet forests. Practically all of this development is being undertaken by owners of commercial timber or pulp companies in the flatwoods area along the Atlantic and Gulf coasts. Along the coast, from the James River in Virginia to the Pearl River in Mississippi, are approximately 20 million acres of forest lands. An estimated 80 percent of the total is wet land. The remaining 20 percent is low but relatively dry sand ridges. Pine trees occupy most of the flatwoods area. Hardwoods grow in the river bottoms and larger swamps.

Since the days of the first settlers, such crops as pine trees have been relegated generally to the less favorable soil sites. Now, though, the commercial value of pine logs has gone up and efforts are made to stimulate their growth on the wet soils. The land

through which the pioneers hurried to escape chills and fever has become important in the production of wood products.

CONSERVATION MANAGEMENT of pine forests is the kind of management that permits the restocking and growing—at an optimum rate for the site—a good species of trees, to which access is available for protecting and harvesting the crop. Producers of timber and pulpwood have found out that the cost of draining wet forest lands will be returned to them through their ability to carry out conservation management even if they receive no other benefits.

In harvesting pine timber from part of a 3,000-acre tract about 2 years after drainage was established, one owner in South Carolina reported that he got an additional net income of a thousand dollars from the use of the larger limbs for pulpwood. That was uneconomical before drainage. Cleaning up the laps, another benefit of drainage, reduces fire hazards.

Restocking the pine stand, naturally or artificially, with a desirable species is often the first purpose of drainage. Even heavy seed falls have failed to catch because poor surface drainage floated the seed away or kept it from contact with the soil. Seedlings cannot survive if they are submerged and scalded during hot weather, and that happens when drainage is poor. In cypress ponds in southern Georgia, no pine seedlings were found before drainage. Within 2 years after removal of standing surface water, the ponded area had reseeded in proportion to the distance from seed trees around the edges. Planted seedlings in the drained pond showed practically a 100-percent survival. Heavy rains produced runoff that covered the seedlings, but the drainage system kept the water moving so that the seedlings were submerged for only a week and suffered no damage.

Favorable results from draining away surface water usually can be seen in reseeding and germination after the first seed fall. Any delay—and it is unlikely—may be due to the absence of seed trees or to ground cover so dense it keeps the seed from reaching mineral soil.

Drainage also makes it possible to harvest timber without costly delays. Logging operations are difficult in many undrained flatwoods forests and sometimes must be postponed because of rains. Special equipment often is needed because of soft ground or excess water on the surface. An operator in South Carolina was able to get back to his logging in a drained forest several months sooner than he could before it was drained and he harvested 1 million board-feet with normal truck equipment. He saved 2 dollars a thousand board-feet over logging costs in similar undrained forests.

In the Deep South, where naval stores are an important byproduct of pine forests, the removal of surface water makes getting around in the woods easier for those doing cupping, chipping, and hauling.

ACCESS ROADS are needed to all parts of the forest for fire protection and logging. If the location of primary and secondary drainage channels has been planned properly, the spoil from the excavation can be smoothed, graded, and made into access roads at only slight additional cost.

The spoil road in organic soils should be capped with a reasonably thick surface of sandy clay or similar dirt. Such a cap tends to retard the oxidation of the organic fill and thereby lengthen the life of the road. An access road built on peat 8 feet deep into the Dismal Swamp in Virginia has been in place for more than 25 years and has lost only a little elevation because of oxidation. It was capped with 12 inches of sandy clay.

The combination of main ditch, berm, and spoil road also creates an effective firebreak.

OBSERVATIONS indicate—but have not proved—that drainage benefits the

rate of growth of certain species of pine. The height of dominant trees, usually after 50 years, is considered a scale—the "site class"—by which to measure the productiveness of a site. Foresters in the slash-pine belt have said that some stands have responded to drainage by doubling in growth over stands on undrained sites. Observations also have shown that a site class of 80 has produced only low-growing, slash pine 6 inches in diameter, after 40 years, apparently because of poor drainage.

Men in the School of Forestry at North Carolina State College have made detailed studies of the influence of drainage on two plantations of loblolly pine on the edge of the Hofmann Forest in Onslow County.

The two plantations are separated by the rights-of-way of Highway 17 and a railroad. A deep drainage ditch is located along the west line of the rights-of-way. The surface drainage of the plantation on that side is influenced by the drain. There is no drain on the east side and no connection is available to provide surface drainage across the combined rights-of-way into the west drain. The east plantation therefore is poorly drained although it is only about 300 feet from the west drain.

Trees in the plantation adjoining the west drain reached a height of 41 feet after 17 years. Trees that were 780 feet from the drain but received some drainage, grew 29 feet. Trees on the east side, planted 1 year later and without benefit of surface drainage, grew to an average height of 16 feet in 16 years. The peeled volume of the stand nearest the drain is nearly 16 times greater than that of the poorly drained stand. Both plantations were on 6- by 6-foot spacing. The east plantation had a survival count of 53.7 percent. The better drained west plantation had approximately 75-percent survival.

Wild game can be benefited by woodland drainage. Removal of surface waters from the woods usually bring about a change in the low-growing types of vegetation. Among the native plants that come into open forest stands after drainage in the Southeast are some seed producers that are attractive to game birds. Add to the natural woodland cover a food supply, and game birds will be the direct beneficiaries of drainage.

Health conditions of the community should receive benefits from the drainage of swampy forest areas. Many flatwoods forests are dotted with swampy cypress ponds, which generally hold shallow water, in which mosquitoes abound. The people in nearby homes, schools, and logging camps receive benefits in physical comfort by the drainage of the ponds.

The adverse effects of drainage probably are less than the beneficial effects. The main objection concerns the loss of the water through the drainage facilities and its possible effect on the water table. Because a flat, waterlogged forest area can store little water from current rains, there must be runoff or flooding. A well-drained forest area, on the other hand, can absorb an abundant amount of rainfall and runoff and flooding are less. Which condition would have the greater effect on the water table is hard to say. The economic advantage is in favor of the forest owner who has drained his land.

The drainage system needs careful planning. The location of main and lateral drains must provide for the best drainage of the forest; make conditions

more favorable to obtain the desired access to the interior areas; divide the forest into areas of convenient size for fire suppression; and assure excavation into stable soils so as to allow the maximum channel capacity to function for a long time.

The size of the main drain depends on the amount of water to be disposed of. In the flatwoods of the Southeast, that amount may vary from 10 cubic feet a second, three-eighths inch in 24 hours, for 1 square mile, to 150 cubic feet a second, slightly less than one-fourth inch in 24 hours, for 25 square miles.

That low coefficient will result in a small channel, compared to one designed to drain cultivated land, because the latter must remove water much faster. If the spoil is to be used for an access road, the excavation may be too light to provide for a satisfactory road fill. Then a larger ditch must be excavated to yield the required amount of fill and the channel capacity for an added degree of drainage naturally results.

The shape of the main channel depends on the kind of soil, the kind of maintenance practices to be used, and the general planned depth of the channel.

In most stable mineral soils and in organic soils, the side slopes of deep ditches may be nearly vertical. In lighter soils, side slopes should be 1:1 or 1:1.5 and as deep as can reasonably be had. A minimum of 4 feet should be the standard. The bottom width should be as narrow as requirements for capacity and spoil permit. A high velocity at low flow is important for operation and maintenance of the channel.

Such cross sections will require maintenance by hand, chemical spray, or dragline. Forest managers in the Southeast generally make no provisions for any particular maintenance, but plan narrow and deep channels, which can be reshaped with a dragline when maintenance is needed. That plan of operation may prove to be the most economical, because drainage requirements are less exact than are those for cultivated land.

Lateral drainage is necessary if the main channels are to function. Water will not move in a shallow sheet across densely vegetated or littered flat land toward a main drain. Small, shallow accumulation channels therefore are used. They need not be engineered as to location or capacity but must be uniform in section and be reasonably easy to locate by a skilled machine operator as they are being constructed. Some types of diskplows, designed primarily for installing firebreaks, are used for the purpose. They cut satisfactory drains on soils firm enough for the operation of a tractor. The fireplow ditch can meander through the forest; it requires a minimum of clearing and does not greatly interfere with established stands.

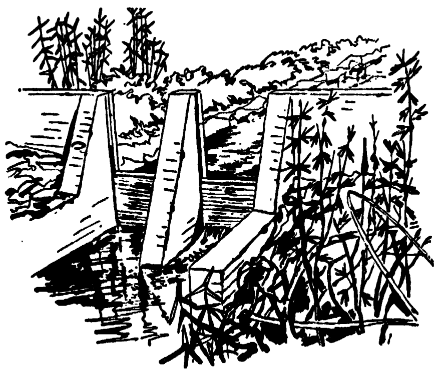
The shallow drain is designed to give direction of flow toward a main or lateral channel. When soils become so unstable that they will not support a tractor, deeper ditches cut with a dragline will be found satisfactory. They may not remove surface water so fast as the smaller, more closely spaced ditches, but, spaced up to one-quarter of a mile apart, they give satisfactory drainage in light and boggy soil.

Pipe inlets are used if a sizable volume of surface water has to be dropped into the channel. They prevent head erosion and the filling of the channel by sediment. If roads are built on the spoil, the pipes will function as culverts. They are extended beyond the ditch bank so that no scouring of the bank will result.

Crossings for trucks are usually constructed of pipe and earth fills with suitable head walls as necessary. They are economical in installation and maintenance, but regardless of how well they may be constructed they are more of an obstacle to the flow of water in the drain than an open-span bridge crossing, which offers less interference

to the flow of water and consequently less turbulence and less scouring of the banks and bottoms of ditches. If culverts are used, the pipe arch section is recommended.

Structures for the control of water levels in deep ditches, designed for manual operation, should be constructed so as not to be endangered by a sudden rise in the water when manual control is not immediately available.



The flashboard type of structure is probably best adapted to this need. Its design should provide for an ample spillway space above the flashboards when they are in place at their highest level. They have been built with reinforced concrete; concrete precast blocks, using steel reinforcing bars and concrete filling of the voids in the block; and braced steel H-columns. All are satisfactory if properly built.

ORGANIC SOILS, when used for the production of timber, will usually require water control rather than uncontrolled gravity drainage. Water control means that the excess water is allowed to drain off as necessary and that residual water from the soil is not dissipated through open gravity drains but is detained by structures.

It is usually necessary to "dry out" the organic soil temporarily in order to be able to follow good conservation management practices. The process is dangerous. Removal of too much water may pave the way for combustion of the soil by flames and by oxidation.

Fires, once started in a dry organic soil, can destroy it along with any trees growing on it. They are unusually hard to put out. A water table established for a period long enough to saturate all of the soil particles and high enough to also extinguish the surface burn is necessary to bring the fires under control.

Oxidation of the soil, as destructive as fire, is more gradual. It does not destroy the growing vegetation and may therefore go unnoticed until much loss has occurred. Dry organic soil profiles have suffered losses of elevation, measured over a long period of years, amounting to an inch a year. A loss of 2 or 3 feet in soil thickness can occur in a generation.

PLANS HAVE BEEN MADE to drain organic soil areas in North Carolina for growing pine trees. One such area, of approximately 150,000 acres, has surface elevations of about sea level to a few feet above sea level. With uncontrolled gravity drainage, such an area can soon lose elevation through oxidation, and it would be impaired for growing pines or any other crop unless excess water were pumped out.

About 1,750,000 acres of organic soils in Virginia, North Carolina, Georgia, and Florida can be classed as being in swamp woods. Not all of it will be drained for timber.

Drainage began on one block of 45,000 acres in Virginia in 1954. Control structures of concrete or timber were installed in all main channels to permit outflow of excess water, or—when closed—to hold up the water in the swamp. Thereby the water table can be lowered in open areas for restocking without waiting for a dry season. Access to all sections over spoil roads is provided for.

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Drainage in the Red River Valley of the North

Walter W. Augustadt

The valley of the Red River of the North, the bed of old glacial Lake Agassiz, is an agriculturally rich basin. Rich—but poorly drained. It is subject to periodic flooding from rapid snowmelt, severe rainstorms, and occasional long wet seasons. The terrain is flat. Natural drainage is poor. Manmade barriers like roads and highways frequently retard natural drainage. Good drainage would be of untold benefit to country and city people.

The Red River of the North, the trunk drainage channel of the basin and the surrounding uplands, forms the boundary between North Dakota and Minnesota. The river proper is formed by the junction at Wahpeton, N. Dak., and Breckenridge, Minn., of the Otter Tail River, which is the outlet for a series of lakes near Detroit Lakes, Minn., and the Bois de Sioux River, which flows out of Lake Traverse in South Dakota. It flows almost due north for its entire length.

On its northward journey to Lake Winnipeg in Canada, the river follows a winding course of more than 450 miles through the central part of a broad, almost flat plain. The plain is 20 miles wide in the southern end and more than 50 miles wide at the international boundary. It is 300 miles long. The river drains a watershed area of 35,895 square miles in the continental United States. Twenty major and minor contributing streams enter the river between Wahpeton and the international boundary.

THE TOPOGRAPHY of the watershed has physical features that bear significantly on flooding and drainage problems.

The fall of the valley from south to north is slight and decreases to the north. Mean sea level elevations at various places along the river point out the variation in fall. The elevation at Lake Traverse is 980 feet; at Wahpeton and Breckenridge, 963 feet; at Fargo, N. Dak., and Moórhead, Minn., 900 feet; at Grand Forks, N. Dak., and East Grand Forks, Minn., 830 feet; at the international boundary, 789 feet; and at Lake Winnipeg, 60 miles north of the boundary, 755 feet.

Thus the river falls 225 feet in 450 miles or at an average rate of one-half foot a mile. The valley floor has the same total fall, but the average rate is three-fourths of a foot a mile, because the straight-line distance is 300 miles.

The slope of the western part of the valley floor, however, is not uniform and varies in direction from south and east to east and north, the larger area having a surface slope to the northeast. A strip of land 4 to 5 miles wide and parallel to the river is the lowest and flattest in the valley. From this strip of land, the valley floor begins to rise slowly at first on both sides of the river at a rate of 1 to 3 feet a mile. That gradient then starts to increase rapidly as the east and west limits of the valley are approached, after which it is not uncommon to find rises of 15 to 20 feet a mile.

The surface aspects begin to change rapidly from flat, almost level land to undulating upland east and west of the plain. Where the central part of the valley varied in elevation from 980 feet at the southern end to 789 feet at the northern end, the upland elevations vary from 1,200 to 2,000 feet above sea level. The width of the area that drains to the Red River in most places exceeds half the length of the drainage basin.

The entire watershed was covered by a continental glacier during the glacial period. The glacier had a marked effect on the topography and extended as far south as Nebraska. When the ice began to melt, the glacier retreated northward. Water from the melting ice flowed south until the edge of the ice sheet had retreated to the south end of what is now Lake

Traverse. From here the valley sloped north; water from the melting ice was trapped between the surrounding highlands and the ice that blocked the northern exit. The trapped water formed a huge lake, now called Lake Agassiz. As the glacier retreated northward, it deposited clay, sand, gravel and boulders up to a depth of 300 feet over the basin. Tributary streams discharging into the lake deposited sediment over the bottom to a depth of 20 to 50 feet, covering the glacial drift in most places. When glacial recession had retreated far enough northward, the lake drained into Hudson Bay. Various stages of lake levels can still be traced by following the beach ridges left by the receding water.

Many of the streams that were discharging into the lake from the uplands to the east and west were probably temporarily blocked from making a direct entrance by the ice. Those streams were then forced to flow south along the edge of the glacier until they could enter the lake around the retreating edge. That might account for the fact that many of the tributary streams flow south for long distances before entering the valley, after which they reverse their direction. Other streams probably of later origin entered the valley directly.

In geologic terms, erosion in the valley is young compared to that of the uplands. Streams from the uplands had been discharging into the lake for a long time and they had cut deep channels. When the lake drained, it did so relatively rapidly, and left the streams without well-defined channels across the lake bed. Many of the streams, after entering the valley, became lost and diffused in the wide flats, and as a result a well-defined natural drainage pattern has not been established. The banks of these coulees and streams after they enter the valley are generally higher than the surrounding land, because sediment was deposited on them when the current slackened during repeated overflows.

Large sections of the valley are so nearly level that flow of water is governed more by artificial barriers than by natural ones. Roads elevated to keep them from blocking with snow in the winter many times divert water from one section to another. Other times they act as dikes which impound the water.

Other large portions of the valley have a fractured system of low intersecting ridges. They are probably tundra ridges, caused during perennially frozen ground conditions. The ridges cause the water to pond in shallow depressions, which make the drainage of individual farms a problem, perhaps bigger than that of constructing the main drainage channels. At one time the entire valley floor may have been covered by the ridges; in areas adjacent to streams the depressions have been obliterated to some extent by sediment deposited in them when the streams overflowed.

Erratic climatic conditions over the years have aggravated the drainage problem. In long periods of drought there is no need for drainage and there may be no ready cash for those who might wish to prepare for the recurring floods. When the floods do return, interest and drainage activities increase, but considerable damage occurs that could have been avoided by earlier action.

The mean annual rainfall in the valley is about 21 inches. About 75 percent of it comes between April and October. The average frost-free period is about 115 days. The climate must be classified as subhumid, but there have been notably wet periods as well as dry. Weather records seem to indicate a tendency toward decided wet and dry cycles. In the first 17 years of weather records, 1861–1877, the average annual precipitation was 24.50 inches. During the next 24 years, 1917–1940, the average precipitation fell to 17.80 inches. From 1941 to 1954, indications were that another wet cycle was occurring. The average precipitation for the first 4 years of that period

was 24.50 inches. In 1944 it exceeded 30 inches.

Averages, however, do not present a picture of weather extremes. Exceedingly dry years occur during wet cycles and wet years occur during dry cycles. The rainfall was less than 13 inches in 1910, yet the period 1878–1916 was relatively wet and on three occasions exceeded 30 inches. Relatively wet years occurred in the 24-year dry period, from 1917 through 1940, but in no year during that period did the rainfall exceed 24 inches. In the extremely dry period, from 1929 to 1940, the average rainfall was 15.50 inches; in 1936 it was only 8.90 inches.

FLOOD DAMAGE has been severe in wet periods. (Requests for help during flood periods usually resulted in the preparation of reports and suggested solutions, which were forgotten during drier weather.) Topographic features of the watershed, along with an immature natural drainage system across the lakebed, made it almost inevitable that the valley would be subjected to very damaging floods during periods of high rainfall.

Serious flooding occurred in 1882 and 1883. The valley was flooded again in 1893. In 1897 one of the worst floods on record visited the valley. The years 1904, 1916, and 1920 also were flood years. Then, after 22 flood-free years, the valley had some of the most damaging floods in its history. The floods of 1943, 1944, 1948, and 1950, and minor local floods in 1952 and 1953, caused losses of millions of dollars each year.

The losses in 1943 and 1944 were so severe that the North Dakota State Water Conservation Commission requested the Department of Agriculture to make a survey of the agricultural damage. Statisticians estimated that 634,000 acres were damaged in six counties on the North Dakota side of the river in 1943, and that the loss was 10,852,000 dollars. In 1944 they estimated that 1,026,000 acres were damaged in 10 counties in the watershed on the North Dakota side and placed the loss at 13,565,000 dollars.

The loss in 1943 and 1944 was in excess of 23 million dollars in North Dakota. The loss in Minnesota was probably as great. From 1943 through 1953, a conservative estimate of the agricultural damage due to floods would exceed 60 million dollars in the part of the valley south of the international boundary. Municipal damage has also been extensive both in the United States and Canada.

Recurring and extended dry periods and the lack of financing during those periods hinder the establishment of an adequate system of drainage and flood prevention. During wet periods requests for assistance were made by individuals and groups, municipalities, counties, and legislators. Plans and reports were prepared; then dry periods reappeared, accompanied by low farm income. The problem is reversed from one of getting water off the land to trying to get water on the land; drainage is forgotten until there is another reversal, and the process is repeated.

The Department of Agriculture in 1905 was requested to help with surveys, plans, and reports for guidance in constructing drainage ditches. John T. Stewart of the Department, with the assistance of the North Dakota State Engineer and financial aid from the counties, completed a survey of five counties in North Dakota. Topographic maps showing the proposed location of ditches were prepared. His report specified the size, shape, and length of the ditches and a cost estimate of the work to be done.

Some of the large drains were constructed from 1907 to 1916, but progress was slow because of intervening dry years and lack of interest. P. T. Simons and Forrest V. King in 1922 prepared Departmental Bulletin No. 1017, *Report on Drainage and Prevention of Overflow in the Valley of the Red River of the North.*

Herbert A. Hard, chief engineer of the North Dakota Flood Control Commission, in 1921 prepared an adminis-

trative report in which he outlined projects that should be constructed. He said: "It is up to the businessman and the farmer to now decide what they will do with said plans. Will they avoid the issue for another 30 years and suffer losses running into millions of dollars?"

Mr. Hard's question could almost have been answered in the affirmative. Practically all drainage activity ceased in the early 1920's. The period 1929 to 1940 was one which is now referred to as the drought of the 1930's.

THE MAINTENANCE of existing drainage ways would have prevented considerable losses. Wind erosion, which accompanied the drought, filled many of the existing natural channels and the drains with soil. There was practically no runoff. The drains, of no use during the drought, were neglected. Grass, shrubs, and trees that became established further choked the channels and helped to hold water and windborne soil. Roads were constructed with little or no regard to drainage. Often no provisions were made for the passage of water from one side of the road to the other. Sometimes the structures were too small to handle the water of a wet cycle. Road ditches discharged with little or no regard to an outlet. Farmers sometimes placed fills across ditches to facilitate their farming operations. Requests were even made to have the Civilian Conservation Corps construct dams in the ditches with the thought that that might alleviate drought conditions.

Twenty-two years without a flood was a long enough period to have a younger generation take over much of the farming operations. Many newcomers came to the valley before and during the drought. Many believed that drainage was a waste of money and not essential to the economy of the area, and longtime residents began to believe that perhaps they were right.

Such were the conditions when the rains came again.

Public demand for immediate action dictated by high flood losses in 1942 and 1943 caused the Department of Agriculture to authorize the Soil Conservation Service to organize its operations to provide technical help in planning and supervising the construction of drainage systems in the Red River Valley. The demand for agricultural production and the high price of farm products made it evident that drainage was necessary to the agricultural economy of a large part of the valley.

Because unified action was deemed advisable, the first step was to set up soil conservation districts. The districts, legal subdivisions of the State, have full authority of State law "to control floods, prevent soil erosion, preserve wildlife, protect the tax base, protect publicly and privately owned land and promote the health, safety and general welfare of the people of said districts."

Fourteen districts were organized in the six valley counties in North Dakota. Four districts were organized in valley counties in Minnesota. After the districts were organized, technicians were assigned to each. The activities were coordinated through area conservationists.

DELINEATING DRAINAGE areas and the establishment of a drainage system for the entire basin was the first step. The work consisted of the construction of new main drains and laterals, the rehabilitation of existing ones, and the establishment of farm drainage on individual farms. The topographic maps that had been prepared for the five counties in North Dakota 35 years earlier by John T. Stewart were invaluable in planning a complete system.

Design standards were established by an engineer to provide technically sound drainage systems. The capacity of ditches for draining farmland is determined by the volume of water that must be removed before crops and land are damaged. The volume is usually expressed as cubic feet per second per acre, and is called the drainage coeffi-

cient. The coefficient is greater for small areas than for larger ones and for the upper part of a drainage basin than for the lower. It also varies with the topography and physical features. Generally it is determined by comparing the conditions in areas that have been successfully drained with those in the area for which it is desired to establish a unit. Trial and studies then lead to values that give reasonable protection at an economically justifiable cost.

Some of the original drains were constructed by using coefficients proposed by Mr. Stewart. They provided for the removal in 24 hours of one-quarter inch in depth for a drainage outlet of 25 square miles, increasing for smaller areas to one-half inch at 4 square miles and decreasing to three-sixteenths of 1 inch at 200 square miles. A study of the drainage area effected by the drains indicated that had the drains been properly maintained they would have given reasonable protection against flood damage. From this conclusion, it was decided to proceed with planning, using the proposed coefficients until further evaluations could be made.

The flood of 1948, caused by the rapid melt of a heavy snow cover, provided a good chance to study the effectiveness of newly constructed and rehabilitated drains. The study indicated that in some cases ditches with greater capacity were needed. Most ditches constructed since then have been designed with coefficients providing for faster removal of the water.

The standards for design call for a minimum flow depth of 4 feet at design stage, with the exception that the depth may be reduced to 3 feet at the upper end when such depth will provide adequate drainage to adjacent land. The minimum bottom width was set at 4 feet, and the side slopes were specified to be not steeper than 2 feet horizontally to 1 foot vertically; 3:1 or 4:1 is considered better. Ditches were designed with a nonerosive velocity of less than 3 feet a second. Spoil banks are leveled out flat enough so that farming operations are carried out to within a few feet of the edge of the drain.

Revision of laws pertaining to drainage by the North Dakota legislative body greatly facilitated the program. It soon became apparent that the existing laws were inadequate. On the reconstruction of old drains the laws limited the expenditure on each drain to 100 dollars except where 60 percent of the assessed individuals petitioned the county to do the job. Sound maintenance operations could hardly be carried out under such a law. It is difficult and time consuming to secure the signature of 60 percent of the landowners affected. An expenditure of 100 dollars is of little value in the rehabilitation of a drainage system.

The law was amended. It is now the mandatory duty of the county commissioners to keep the drains open and in good repair. The cost of maintenance is levied and collected in the same manner as required for the original construction. Under the law, the levy for any one year shall not exceed a maximum of 50 cents an acre on the lands in the drainage district.

A fund may be accumulated by the county commissioners for the purpose, but the fund shall not exceed the maximum allowable levy for any year. The county board must contract for the job to the lowest responsible bidder. The laws were also revised to permit county commissioners to enter into a contract with soil conservation district supervisors if, in their opinion, the work could be done more cheaply with equipment operated by them. The act also provided that if funds accumulated by assessment are not sufficient to finance the proposed work, that on petition of property owners liable for 10 percent of the cost of the work, the county commissioners are required to hold a hearing. If property owners liable for 51 percent of the cost agree to the project, the commissioners are authorized to proceed.

The North Dakota Legislature in 1949 also amended the law on voting

rights or power of landowners in establishment of a new drain. Under the old law, landowners had equal voting power regardless of the amount of liability for assessment. The new law provides for a reasonably fair relation between the amount of liability for assessments and the power of objecting to the establishment of the drain. The voice or vote of affected landowners is arrived at in the following manner: Each landowner has at least one vote or voice; in addition, each landowner has an additional voice or vote for each 100 dollars or major fraction thereof of assessment that his land is subject to as established by the drainage board.

Those and other changes made it easier to carry out the program.

Financial aid by the State of North Dakota helped. Recognizing that immediate construction of drainage work was necessary if land in the valley were to approach its agricultural potential, the Legislature appropriated money to speed up construction of new drains and reconstruct existing ones. The money was appropriated by periods as follows: 1943–1945, 50,000 dollars; 1945–1947, 240,000 dollars; 1947–1949, 200,000 dollars; 1949–1951, 150,000 dollars; 1951–1953, 90,000 dollars; 1953–1957, 140,000 dollars.

The money was made available to legal drainage districts on a 60 percent to 40 percent basis. After the chief engineer of the State Water Conservation Commission approved the plan, the State allocated 40 percent of the cost of the project to the drainage district. That financial aid was of great help in getting projects under construction and completed. Of the 810,000 dollars appropriated, 752,450 dollars had been expended or obligated in 1954. The remainder was held in reserve for special or emergency needs.

The Department of Agriculture recognized that good conservation practices could not be carried out on lands that were subject to periodic flooding. Through agricultural stabilization payments, it provided funds to be used for establishment of farm drainage systems.

The amount of work to be done in North Dakota, as proposed by Mr. Stewart in 1906, called for the construction of 1,820 miles of mains and laterals. He estimated that this construction would cost 3,048,342 dollars and would benefit 1,480,260 acres. No estimate was made for Richland County, which, if it were included, would require the construction of more than 2,000 miles of mains and laterals; more than 1.75 million acres would be benefited. No estimates were made of the amount of individual farm drainage that would be needed.

Up to 1944, 697 miles of the drains had been constructed. Most of the construction had been carried out before 1920, and practically no maintenance work had been done. All the drains had to be surveyed and designed for reconstruction. New drains also had to be designed, established, and constructed.

The manner of processing plans and contracts resulted in fast action. The Soil Conservation Service furnished engineers to the districts to make surveys, prepare plans, and supervise construction. After legal requirements of establishing a new drain or reconstructing an old one were met, the plans were submitted to the State Water Conservation Commission for approval. When the plans were approved, contracts were let by the drainage board or county commissioners. The State sets up a fund equal to approximately 40 percent of the construction cost; as construction proceeded, vouchers were prepared by the drainage board or commissioners drawing on this fund. The remaining 60 percent of the cost was assessed against the land benefited in proportion to the amount of benefit received as established by the drainage board at hearings held for that purpose.

The first few years the program was

in operation, work on main drains far exceeded work on individual farm drains. This was natural because it was first necessary to provide a system of outlets. Also, landowners not familiar with problems involved in drainage generally believed that all that was needed was a main drainage system. As the program progressed, however, the volume of farm drainage work began to exceed that done on main drains; many farmers spent 2,000 or 3,000 dollars on a quarter section to get an adequate drainage system. The volume of work to be done on this phase of the drainage program far exceeds the work to be done on mains and laterals. Because farming conditions are carried out with large machinery and across the ditches, farm drains are constructed with very flat side slopes and wide bottoms. Most of the ditches have an 8-foot bottom width; side slopes are 8 feet horizontally to 1 foot vertically.

CONTRACTS LET during the war years were high because many contractors were working on defense plants and little construction machinery was available. The Department of Agriculture made machinery available by lending it to soil conservation district supervisors. The machinery was operated by them during the war years and cut costs of drainage.

As the volume of work increased and more machinery became available, more contractors became interested. The resulting competition resulted in lower prices. The supervisors of the districts returned the machinery that had been on loan to them and no work has been done with Government-owned machinery since 1950.

THE ACCOMPLISHMENTS of the program can be measured by the amount of work done. In 10 years, a total of 3,176 miles of drains were constructed, involving the movement of more than 18,600,000 cubic yards of earth. Of the 2,000 miles of mains and laterals needed, 963 miles involving movement of 10,252,699 cubic yards of earth were constructed and rehabilitated. Individual farm drainage amounted to 2,213 miles and 8,347,301 cubic yards.

Participation of the North Dakota State government through its legislature and its State Water Conservation Commission, the soil conservation district supervisors, the Soil Conservation Service, the Agricultural Program Service, other Federal agencies, boards of county commissioners, county drainage boards, township boards, and the Red River Valley farmers developed into a highly cooperative program that has produced beneficial results.

The remaining work that needs to be done on this project exceeds the accomplishments. Up to 1955, about half of the large legal drains needed had been constructed. The volume of earth movement needed to establish adequate individual farm drainage will far exceed that required for the construction of mains and laterals. How fast the whole program continues to progress will depend on the incomes of farmers and the financial and technical aid available.

To keep excessive moisture from causing heavy damage to crops and land in the Red River Valley, two problems must be solved. One is flood control. The other is drainage.

In some respects the two problems tie in so closely that it is doubtful if they can be solved separately. The wide, flat bottom of the valley makes construction of drainage ditches a necessity. Storms, local in nature and occurring within the valley itself, often damage crops severely unless drainage is provided.

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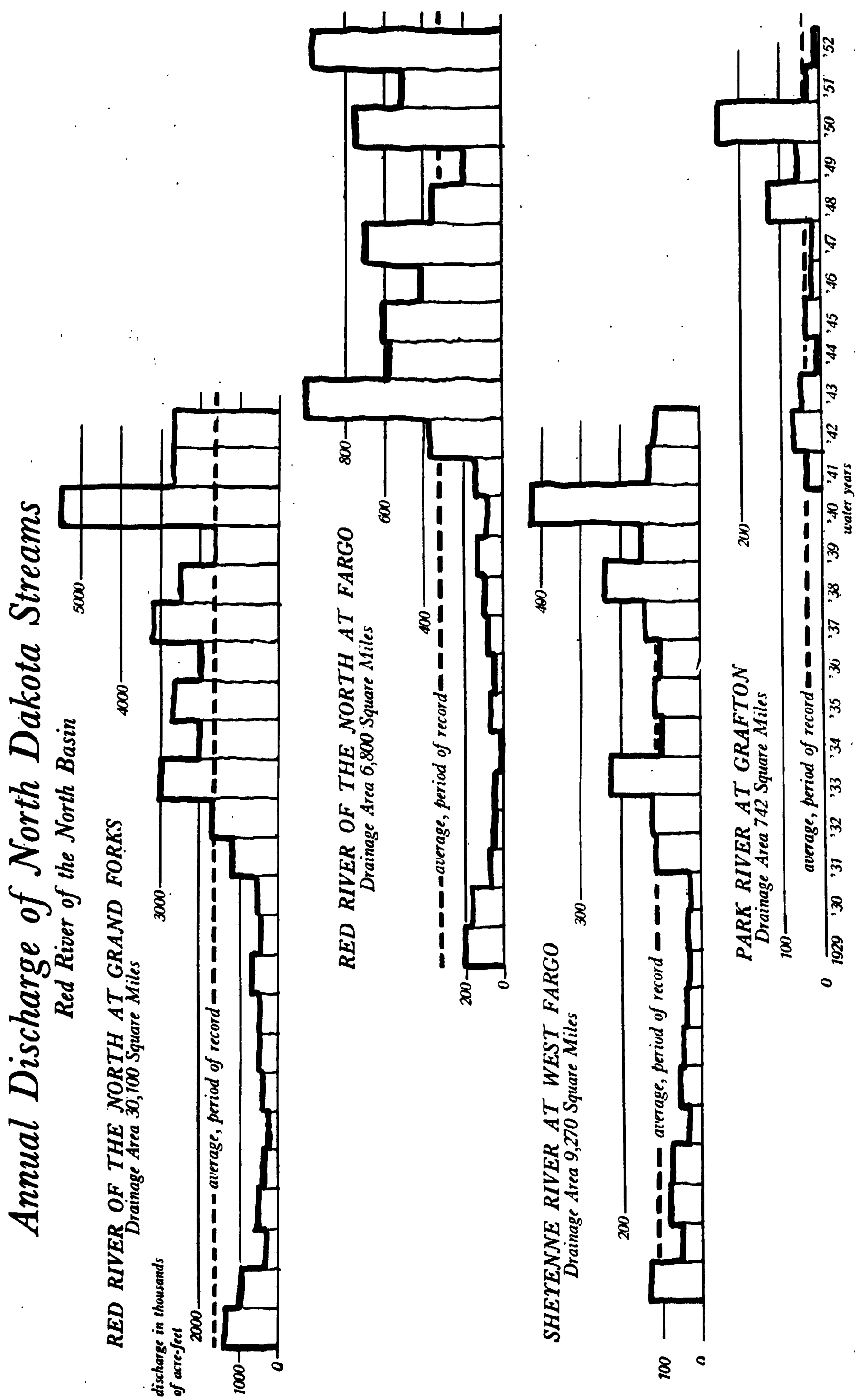
Annual Discharge of North Dakota Streams
Red River of the North Basin
RED RIVER OF THE NORTH AT GRAND FORKS
Drainage Area 30,100 Square Miles
discharge in thousands of acre-feet
0
1000
2000
3000
4000
5000
average, period of record
RED RIVER OF THE NORTH AT FARGO
Drainage Area 6,800 Square Miles
0
200
400
600
800
average, period of record
SHETENNE RIVER AT WEST FARGO
Drainage Area 9,270 Square Miles
0
100
200
300
400
average, period of record
PARK RIVER AT GRAFTON
Drainage Area 742 Square Miles
0
100
200
average, period of record
1929 '30 '31 '32 '33 '34 '35 '36 '37 '38 '39 '40 '41 '42 '43 '44 '45 '46 '47 '48 '49 '50 '51 '52
water years

Water and Our Wildlife

Planning for the Recreational Use of Water: A Plea

John H. Sieker

Many popular recreation areas in the United States owe their attractiveness to water—Niagara Falls, Lake Tahoe, thousands of lakeside resorts, and an uncounted number of streamside picnic spots.

But because of inadequate planning, other uses of water often conflict with the recreational use. The recreational value of water can be impaired by pollution. Diversion of water for industrial or irrigation uses may often destroy recreation values. Unless better multiple-use planning for land and water is practiced, many existing or potential recreation values will end.

Watersheds should be protected from erosion and should be managed so as to provide a maximum of clear water with a minimum of flash runoff and silt. The stream banks and shores of reservoirs should be free of all unnecessary developments. But that does not mean that all recreational use has to be excluded. Under present conditions, few cities can dispense with filtration and chlorination; if those installations are properly engineered and supervision is adequate a city watershed can be used for picnicking, boating, and fishing without endangering the health of the citizens. It can thus do double duty.

The returns in human health, welfare, and happiness should more than offset the cost of eliminating industrial and sewage pollution. The recreation potential of the land along many rivers, such as the Ohio, Cumberland, Hudson, Potomac, Mississippi, and the Missouri, would be enormous if they were not polluted.

As A RESULT of single-purpose thinking, recreational values of water may be unnecessarily destroyed or impaired by power projects or by flood-control and irrigation reservoirs. Hundreds of miles of fine fishing streams have been flooded by reservoirs. A reservoir, when full, may have as much recreation value, although of a different kind, as the streams it flooded, but often the reservoir is only partly filled during the height of the recreation season. A half-full reservoir with wide mud flats is not pretty. Its fish production capacity is usually low because the fluctuating water level destroys fish food and the higher water temperature at low levels may be detrimental to game fish.

Many miles of good fishing streams are dry in the summertime because their water is diverted for irrigation and power. Good recreation areas may thus be destroyed below a reservoir or diversion weir in addition to recreation values destroyed through flooding by the reservoir itself.

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The American economy will require increasing numbers of power dams, irrigation reservoirs, flood-control projects, and diversions of water for municipal or industrial use. But there will also be increasing need for outdoor recreation. The importance of recreation requires that consideration of recreational values enter into the overall decisions as to the use of water. Recreational values may outweigh the value of a proposed industrial use in some places. Often some of the recreational values can be preserved by appropriate planning and management. Recreationists have the right to demand that realistic values be placed on water for recreation and that all plans for its management consider those values.

An acre-foot of water with a 100-foot head may be worth 4 dollars for power and another 5 dollars for irrigation after the kilowatts have been extracted. A good-sized reservoir might hold half a million dollars worth of water, based on those values.

Suppose, though, that such a reservoir flooded 15 miles of recreation streams and that the diversion dried up another 10 miles of stream below it to the extent that fishing and other recreation were destroyed. If that 25 miles of stream were capable of providing 250,000 man-days of recreation annually before the reservoir was built and the reservoir, because of fluctuating levels, afterwards attracts only 50,000 visitors a year, what would be the value of the recreation lost? At a dollar or two a day, it would be more than half the value of the water for irrigation and power.

An impoundment does not necessarily have to take all the water from a river. In several instances where impoundments have been made within national forests, the Forest Service has required power companies to release not less than 50 second-feet during the high-recreation months, June, July, August, and September. Fifty second-feet is approximately 99 acre-feet a day. That means releasing water worth 2,770 dollars a week for power.

If 10 miles of recreation area and fishing stream can be maintained for 2,770 dollars a week, how many people must use it to make it profitable from a public-use standpoint? It would not be unusual for 10 miles of good fishing stream running through attractive forest to receive recreation use by 10,000 persons a week. Thus, if the recreation use were worth only 28 cents a day, the public would receive its money's worth. Most people would appraise a day's recreation at more than a dollar.

A careful weighing of the relative values of recreational and other uses of water may show that it is worthwhile to delay the drawdown of a reservoir so as to have it reasonably full during the peak recreation months. By a combination of flood storage during the spring and retarded drawdown until after Labor Day, many reservoirs could be managed to provide good recreation and fishing in summer. The loss in water value for power or irrigation can be accurately calculated; the gain in recreational value likewise can be ascertained. Both should be appraised to determine what will bring the greatest total of values to people.

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At least three billion tons of solid soil materials are washed out of the fields and pastures of the United States each year by water erosion alone. It has been figured that to move such a bulk of American soil on rails would take a train of freight cars 475,000 miles long—long enough to girdle the planet 18 times at the Equator.—RUSSELL LORD

The word "conservation" in its present meaning was unknown until the early part of 1907. It occurred to me one day that forestry, irrigation, soil protection, flood control, waterpower, and a lot of other matters which had up to that time been kept in separate watertight compartments were all parts of one problem. That problem was and is the use of the whole earth and all its resources for the enduring good of men.—GIFFORD PINCHOT

Managing Watersheds To Provide Better Fishing

Herman F. Olson, O. H. Clark, and
D. John O'Donnell

The 30 million Americans who go fishing every year and the 30 million others who would like to fish ask a worried question, "What's happening to our fish and our streams?"

Here are three examples of what has happened.

Southern Wisconsin has lost much of its stream trout fishing because of the effect of land clearing, farming, and grazing. Limited fishing is provided on a put-and-take basis—trout are planted with the intention that anglers will catch them before the fish succumb to the poor conditions.

The Whitewater River and its tributaries in southeastern Minnesota once provided 150 miles of good trout water. In 1941, only 60 miles of stream supported trout, and that was in poor condition. Improved watershed management has increased this to 80 miles.

The clear, spring-fed streams of the Missouri Ozarks have been subject to severe floods after a century of destructive land use. Logging, habitual burning of woods, farming, and heavy grazing have hurt the watersheds. A drought from 1951 to 1954 ended the floods, and proved to be less damaging to fish habitat than the periodic floods.

Such conditions and studies of fish and lakes and streams have established that good fishing depends on a good water habitat, which furnishes the food, cover, and other requirements that fishes need to thrive. Conditions of streams and lakes depend in turn on the condition of the watershed of which they are a part. So the planting of fish and restrictive fishing regulations, which once were considered the remedy, are giving way to the management of habitat and watershed as the most promising solution to the problems of maintaining our resources of fish.

Fishermen generally have agreed with this analysis and solution. Many of them have seen the decline of fishing in a favorite lake or stream and have associated it with changes resulting from misuse of the land around. They have seen how floods may scour out plant and insect foods and destroy spawning beds and choke the stream with sand and silt. Or they have seen how excessive runoff of rain keeps the watershed from absorbing enough water to replenish the streams between rains, so that the flow is reduced to the extent that fish are confined to limited sections and so suffer shortages of food and exposure to predators.

Sometimes the streams may become intermittent and lose all fish. The reduction in the flow of springs and the loss of streamside shade may raise the temperature of streams above that required by trout. Increased erosion on the watershed may accelerate sedimentation in lakes and reservoirs and produce a habitat in which only rough fish can live. Winterkill of fish may result from the lack of oxygen, which often develops in such shallow, weedy waters.

The fertility of fishing waters reflects the fertility of the watersheds from which they come. Loss of fertility through clear-cutting, fire, overgrazing, and destructive farming practices reduces the production of fish as well as the yield of land crops.

Under primitive conditions grass and trees covered practically all land surface. The excellent watershed conditions meant clear, productive streams. Enough water entered the soil to feed springs and seeps and maintain the flow of streams.

The changes in the past few generations require only brief mention. Agricultural development has removed the permanent cover of grass and forests from about 400 million acres of land, which are devoted to row crops. An additional 900 million acres of native grass and forest lands have been stocked with domestic animals. Cover

on some of it has been greatly reduced and the soil trampled and compacted to the extent that it absorbs water less well.

Clear-cutting of large tracts of forests, removal of stream shade, slash fires after logging, and the use of streams for log drives reduced cover, destroyed litter and topsoil, and lowered fertility. The poorer watershed conditions have affected not only our agricultural and forest economy but also the recreational fishing resource.

Pollution by the discharge of industrial and domestic wastes into streams and lakes has also been a major destroyer of fish habitat. Its importance has increased with the growth of population and the expanded industrial development. The problem is becoming one of shame and urgency in many places. The control of pollution is an important factor in the fisheries aspects of watershed programs, but it must be handled separately from the land-management phases.

GOOD CONDITIONS can be restored through the understanding management of watersheds. A number of developments indicate an encouraging reversal from destruction to restoration of habitat.

The increased emphasis and interest in the management of privately owned forest lands is an example. Proper cutting practices, protection from fire, and the reforestation of burned-over and abandoned farmlands are effectively restoring good watershed conditions on this type of land.

Fishing opportunities are being increased greatly through the construction of reservoirs for storing water. These vary in size from a farm pond of less than an acre to lakes and flood-control reservoirs. Generally they all serve several purposes at once. They are good for flood control, wildlife, stock watering, swimming, boating, camping, and picnicking.

THE SPRING CREEK watershed in the Missouri National Forest illustrates the beneficial effects of land management on a stream. When this area of 5 thousand acres was purchased by the Forest Service in 1935, it was typical of southern Missouri's Ozark hills. Timber occurred in open stands of low-grade trees that had burned.

Livestock raising furnished a precarious livelihood for the local people because forage was depleted after a century of heavy use. The woods were burned over periodically in the mistaken belief that burning was necessary to produce grass. The ground was barren of leaves and litter. Erosion of the topsoil had exposed the chert stone common to Ozark soils.

Spring Creek flooded with every heavy rain, and gravel washed in from the hillsides and choked the streambed. The springs and seeps ceased to flow. Spring Creek became an intermittent stream, completely dry if frequent rains did not supply surface runoff. Fishing was practically nonexistent.

Good management brought a change. The area has been given excellent fire protection. The timber stands have been improved by cutting and girdling the cull trees of no commercial value. Trees have been planted. Grazing was controlled. The leaves and branches left on the ground have restored fertility to the extent that myriad insects and associated animals again find a suitable habitat. They burrow into the soil and mix the decomposing litter with it. Grasses, herbaceous plants, trees, and shrubs have increased in density.

The improved vegetative cover intercepts rains. The litter acts as a sponge in absorbing it. The porous soil soaks up the excess. Infiltration tests have shown that such reconditioned soil will absorb 2 inches of water in fewer than 3 minutes, compared to 1 hour or more for similar soils subject to burning and misuse.

Spring Creek began to flow yearlong. Even in 1954, following 3 years of record drought, it had enough water to support fish, although short sections merely trickled through gravel beds made by past floods.

In several States fishermen are convinced that good watershed management programs are essential to good fishing, and have encouraged their conservation departments to engage in the organization of programs to develop small watersheds. They approve the use of revenue from fishing licenses for this purpose as an investment in maintaining sport fishing.

Michigan and Wisconsin have initiated watershed programs, which are worth special mention as examples of participation by sportsmen groups.

IN MICHIGAN the work is conducted by the State Department of Conservation. The program was started in the summer of 1950 on the Rifle River in Ogemaw County. It covers 180,000 acres, one-third of which is in private ownership and two-thirds in Federal and State ownership.

Provision was made to finance this and subsequent watershed development units with funds from the sale of fishing licenses. For the first part, 200 thousand dollars was allocated. In the 1954–1955 fiscal year, 360 thousand dollars was made available for watershed development work. Three units were completed between 1950 and 1955. Two others were started.

Great credit for the success of the work goes to the policy of allowing work to be done on private property—most of it farmland—where benefits will accrue to the watershed, as judged by surveys.

A simple permit to allow access for work crews and the maintenance of structures is all that is requested of the owner, but he agrees not to disturb or cut plantings of trees for 10 years. He agrees not to destroy stream structures or fencing, but he is not required to let fishermen or hunters enter his property. The arrangement has solved many of the problems connected with public work on private lands.

Cooperative effort is encouraged and provided by the many interested organizations and agencies, among them the Forest Service, soil conservation districts, and the Geological Survey. The local groups participate in the formation of steering committees, who meet at intervals to discuss methods for developing the project.

A statewide watershed survey was begun in 1952 to determine the extent of the problem areas, remedial action, costs, expected results, and the economic feasibility, as measured by the benefits to fishing.

Each part of the survey begins with a rapid reconnaissance of the stream system and uplands in order to assess the need for further information. If a need for action is found, a detailed survey is made of the drainage pattern, erosion conditions, ownership, farming methods, cover, recreational uses, and water temperatures and flow. If a work project is then indicated, a construction plan is developed that can be used by the field crews.

The list of surveyed streams permits the setting up of a priority system based on known conditions and problems of the watersheds on which inventories were made.

The completed plans are turned over to the field supervisor, and work begins. Usually a field office is constructed or moved to the operating region. Local labor is hired when possible.

The field work is in two categories. The first includes upland work in cooperation with the farmers and involves farm plans based on recommendations of the Soil Conservation Service, tree plantations, waterways, retention ponds, and other measures to conserve soil and water. The second includes the construction and improvement of stream channels.

In counties that are organized and operating as a soil conservation district, the farm plans are prepared by the farm planner of the Soil Conservation Service. In the other counties the land-use planner of the State Department of Conservation makes the plans. On land through which streams flow, fencing along streambanks, with access points for livestock, is advocated. Planting trees for shade and protection

inside the fences is recommended and is done without cost to the owner. A permanent maintenance program is set up.

Three procedures were set up for planting trees beyond the stream borders. Lands that directly contribute runoff sediments to the streams are planted, fenced, and maintained by the State. The parts of the farms that are not critical to the flowing waters are planted by the landowner, and the stock is furnished without cost to the farmer. On noncritical areas, such as a timber stand to be converted to a more valuable tree species, the State will arrange to get and deliver the stock to the owner, but the farmer must pay for the planting stock and the cost of planting. Planting equipment is rented to him at a small fee. Waterways considered critical to the streams are designed, constructed, and maintained by the State. Stiles that the landowner wants for the convenience of fishermen are placed and maintained by the Department of Conservation.

Trained crews do the work of improving the channels. It consists largely of structures of the deflector type, bank protectors, and covers. Rock, if it is available, is preferred as a bank-stabilizing material and is placed after dressing back the critical bank angles. The zone above high water is seeded to grass or sodded. Power shovels are used to grade banks and excavate pools in places where the stream bottoms are hard.

Two small stream systems have been set aside for experimental determinations of rainfall, amount of runoff, fluctuations in ground-water levels, and soil losses. Automatic recording gages are used for determining rainfall, volume of streamflow, and temperature.

Cooperation with the Geological Survey in financing the streamflow recorders is an integral part of the program. A number are on small tributaries. They provide data on changes in streamflow that may occur because of improved land use. They have recording thermographs to collect the data on the changes in average stream temperatures. Periodic checks are made to ascertain the changes in the pattern of land use.

In Wisconsin the watershed development program emphasizes participation by all divisions of the Conservation Department and enlists the support of all groups interested in watershed management—public agencies, landowners, town and county officials, and service organizations.

Four public agencies cooperate in all the watershed programs, operating under a joint agreement that lists the responsibilities and assistance available from each agency. The agencies are the State Soil Conservation Committee, the Soil Conservation Service, the University Agriculture Extension Service, and the Wisconsin Conservation Department.

A watershed association is organized to enlist and coordinate the interest and effort of landowners, town and county officials, and local service organizations. Its officers and directors are elected. They work with the public agencies in planning for the development of each acre in the watershed.

The program approaches the conservation of the State's natural resources through the management of small watersheds. The basis is the understanding that all phases of conservation of soil, water, forests, fish, and game will receive attention to the ultimate benefit of the landowner, the community, and the State. Thirty-nine watershed associations operated in 1955.

The program is an outgrowth of a stream-habitat development program started, with a budget of 10 thousand dollars, by the Fish Management Division of the Conservation Department on a demonstration basis in 1948. Work on a second stream was started in 1949. The Conservation Commission approved a statewide watershed development program in 1950. The Fish Management Division was given primary responsibility for the program.

The Conservation Department cooperates in making basic surveys on the need for and possibilities of watershed developments; advises and assists the landowner in establishing plantings of trees, windbreaks, shelterbelts, and wildlife food and cover; and advises on the care and protection of woodlots from fire, insects, and disease and on the harvesting and improvement of timber stands.

Protection of the waterways is given early attention so as to reduce erosion damage while conservation practices are being applied on the watershed. A protection zone 1 to 10 rods on each side of the stream is leased from the landowner for 20 years, with option to renew for 20 years at a nominal sum. The lease provides for protection and development and for access by the public. First priority is given to fencing the streamside strip. Provision is made for any cattle-watering places and stream crossings that the farmer may require. Trees and shrubs are planted to stabilize banks and provide streamside shade and food and cover for wildlife. Bare areas are seeded to various types of soil-holding grasses.

Stream improvements for fishing may include structural developments like deflectors, covers, retards, and bank developments of various types. They help to provide the basic requirements of fish for cover, food, and spawning areas, and suitable water temperature.

The State employs a dozen field work crews to do this kind of work. Many improvement projects are completed by 65 civic and sportmen's groups. Plans, supervision, tools, and materials are provided by the Conservation Department as needed.

Cooperating groups have given some help, usually in planting trees, to the landowner. Better farmer-sportsman relations have resulted. The sportsman also benefits by improved fishing and hunting. Studies of fish populations have shown that their numbers have increased in the improved streams.

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Making New Trout Streams in the Sierra Nevada

Fred P. Cronemiller

Small, inexpensive dams have made many fine trout streams where none existed before in the Sierra Nevada of California.

Streamflow in this mountain chain is normally very low in summer; most of the smaller tributaries become completely dry. The native rainbow trout survives the summer in lakes, in the larger tributaries, in spring-fed pools, and at the highest elevations where the late-melting snow pack maintains some streamflow. But natural spawn is mostly lost when the streams dry up, and fishing becomes mediocre at best. To store water for a regulated summer flow in these streams, small dams have been designed and given the distinctive and accurate name, flow-maintenance dams.

Climate and geology of the Sierra Nevada make the dams necessary. At Redding and Kernville, near the opposite ends of the Sierra Nevada, less than 5 percent of the annual precipitation occurs between June 1 and September 30. There just is not enough water to maintain the streams without storage of winter precipitation, and a good deal of the mountain range is too rocky to store much water underground. Glaciation left the higher parts of the mountain chain a more or less barren expanse of sculptured rock and rock fragments of little water-holding capacity. Snowmelt prolongs spring runoff into June or July, but for the rest of the summer streamflow depends on the limited supply of ground water.

The glacial action that created the alpine basins left several hundred lakes, many of which can be dammed without great expense. Their outlets usually are at bedrock and a minimum of excavation is required. Unit costs for storage are low because a large amount of water is stored behind each foot of dam height, whereas reservoirs in the normal, steeply sloping drainage channels have little storage capacity for the first few feet.

The area in which glaciated basins occur is mostly between 7,500 and 9,000 feet in elevation. Below 7,500 feet topography is more dissected, and streams slope down steeply and continuously with little opportunity for inexpensive storage. Above 9,000 feet, snowmelt is slow and streams hold up better. But the topography is more rugged, cascades limit the movement of fish for spawning, and soil suitable to maintain the natural food chain and other requirements of a productive trout stream is at a minimum.

Three areas in the Sierra Nevada lend themselves admirably to the installation of flow-maintenance dams: The Toulumne drainage on the Stanislaus National Forest, the American and Truckee River drainages on the Eldorado National Forest, and the San Joaquin drainage on the Sierra National Forest. Elsewhere in the Sierra Nevada topography is too rugged or development too expensive on most of the sites.

The Cherry Creek drainage, tributary to the Toulumne River, has a runoff pattern typical of the glaciated granite country of the High Sierra.

In the upper tributaries of Cherry Creek are more than 80 miles of potential trout stream. A stream gage is installed at the elevation of 4,500 feet, above which is a drainage area of 111 square miles. About 80 percent of the area lies between 7,500 and 10,000 feet. The total runoff in a typical water year, such as the one that ended September 30, 1949, is 214,400 acre-feet. Snowmelt began early in April 1949. The measured flow rose from 140 cubic feet per second (c. f. s.) on April 1, to more than 1,000 c. f. s. on April 12. From then until mid-June the flow mostly was between 1,000 and 2,000 c. f. s. Then it dropped steadily—to 32 c. f. s. by July 15 and 10 c. f. s. by July 30. In August and September low flows of 5 c. f. s. were recorded, and the smaller tributaries dried up. In October the flows increased enough to maintain fish life.

Fluctuating streamflow has created problems in California since the early Spanish Missions first diverted water to their gardens and farms. Soon after gold was discovered in 1848, miners found that deficient summer flows made it necessary to store water to extend the period of mining operations. Irrigation and hydroelectric developments later required the storage of vast quantities of the winter and spring runoff to supply water for summer.

Fred Leighton, of Sonora, Calif., an ardent fisherman and conservationist, was the first to apply the principles of water storage to improve fishing. His desire to prevent the annual loss of thousands of fingerling trout in a small stream on the Stanislaus National Forest prompted him in 1925 to construct a small dam on a headwater lake. The dam is still functioning, and the release of its stored water through the dry summer has developed a permanent stream with excellent fishing.

After the success of the first project, funds were raised for the construction of five other structures in 1931. Money and the materials came from several sources: Sportsmen's clubs, cities, counties, the State Department of Fish and Game, and the Forest Service. In the 1930's several projects were completed under emergency programs of the Forest Service. Since the Second World War the construction of flow-maintenance dams has been financed principally by the State Department of Fish and Game.

In 1954, 40 dams had been installed. They store 11,295 acre-feet of water. They cost about 150 thousand dollars. Roughly half of the dams were built before the Second World War at the cost of about 5.75 dollars the acre-foot of water stored. Since the war, costs have approached 25 dollars the acre-foot of storage. The increase was due to a trebling of unit costs and to the fact that dams were built on the more economical sites early in the program.

Before the dams were built, the areas they served were not attractive to fishermen and few fished there. Trout were abundant in only a few lakes and were usually of a single age class, reflecting a wet year when streamflows were adequate to make spawning successful.

Spawning now is most effective, and streams and lakes are well stocked. Production of food for trout has increased, and the number and size of fish are larger. Fishing effort has increased manyfold—and so has each fisherman's catch.

The cost of the natural "trout factories" is less than the equivalent hatchery installation. The maintenance costs practically nothing. Nature picks up the check for the annual production costs, the major item when fish are reared artificially.

SEVERAL FACTORS must be considered in determining the merit of proposed flow-maintenance projects. First, of course, there must be a demonstrated need—a showing that fluctuating water flows have reduced or eliminated possibilities for trout production. Second, there must be the possibility of storing enough water to maintain the needed flow. As a general guide, a dam or dams in series should provide for the storage of at least 100 acre feet of water. That would result in a flow of 0.5 cubic foot a second for 100 days, but the flow usually is somewhat less because of evaporation in the reservoir. A flow of that size usually insures the survival of spawn. In places where springs and seepage contribute water downstream less than 100 acre-feet of storage might be helpful. Some projects can be developed therefore even where storage sites are limited.

The ideal situation exists in places where reservoirs can be developed in series or where a reservoir can be developed above a natural lake. Two or more lakes in series provide habitable water and insure productive spawning area between the lakes. That is the case in 14 existing projects. A similar situation exists where a low dam will maintain the flow of a tributary to a large stream capable of assuring a source of spawning fish.

The best fishing, of course, is usually in the downstream lake. The fish are larger and have the advantage of the regulated flow and spawning areas. While streams are essential to almost all trout spawning in the areas, the value of the 337 miles of developed stream for fishing should not be set too low.

The cost of any clearing must also be considered in determining the feasibility of a project. The lower part of the glaciated area is within the range of the lodge-pole pine. If raising water levels will flood a large area of this densely growing tree, an expensive clearing job will have to be done and the project might be uneconomic.

The effect of the development on trout foods is important. Increasing the water depth over marshes and flooding meadows may increase food. Increasing the depth of lakes with steep shores and little shallow area usually reduces

food production, however. How a dam affects the ability of a lake to produce and grow fish may be a deciding factor in choosing between sites.

Much of the area in which flow-maintenance dams are feasible is a natural wilderness, and parts have been formally dedicated as such under regulations of the Secretary of Agriculture, which govern administration of the national forests. Because wilderness areas have no roads and few trails, artificial restocking rarely is practicable. Then natural reproduction of fish becomes an essential phase of each project. Spawning gravels must be available to each project. Dams may create a barrier to trout movement to downstream spawning beds, but the benefits of regulated streamflow downstream may more than offset the loss created by the barrier.

Many feasible reservoir sites include meadows with high forage values that would be lost on flooding. Some meadows may also have esthetic values worthy of consideration. On the other hand, some projects raise water tables along the reservoir margins, and the result is increased forage production. Most fisherman and campers reach the alpine basins by saddle and pack stock. Providing forage for their animals has required consideration in a few areas.

Most projects increase the attractiveness of the mountain area. The beauty of all streams is enhanced. Construction work is done with concern for preserving natural conditions. Most of the dams are built of native stone, and their exposed faces are made irregular to blend with the local surroundings. The main trails often detour the dams so the traveler is not conscious of any artificiality.

STREAM IMPROVEMENT throughout the Nation has been marked by few outstanding successes. Probably the best of them are the flow-maintenance dams in the Sierra Nevada. They have increased the water area of some 40 lakes.

The improved water flows have helped reduce flood peaks and contributed additional water during critical periods downstream, a fact appreciated by power companies, irrigators, and municipalities.

The end of the work was in sight in 1955. The number of known worthwhile projects that remained probably did not exceed the number already completed. Engineering and biological studies were being continued, and priorities were being set for completing the program.

The wilderness character of the Sierra Nevada, with its limited accessibility, should continue to regulate the numbers of fishermen and their catch. Nature will no doubt continue to replenish the trout streams that man has helped her provide.

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The Need of Wildlife for Drinking Water

Lloyd W. Swift

Many of us recall seeing wild animals come to the waterholes in dry periods and in arid sections. Our memories may include the disturbance created by a sudden invasion of a watering place in the heat of the day. There is a burst of life, a flapping and whir of wings, rustling of leaves from scurrying feet and calls of frightened birds. Or we may remember sitting quietly at a waterhole some summer evening. Then the animals usually approached, cautious, wary, alert.

But some we did not see: There are many species of wild creatures that seldom are seen at watering places—the opposite of the fish and other animals that live in the water, the frogs and other amphibians that must spend a part of their life cycle in water, and those, like the beaver, that are in and out of the water. One cannot generalize about the need of wild animals for water. Some apparently obtain all they need from the succulent vegetation or soft-bodied insects they eat.

When their food supply becomes parched, these animals often need free water. Some animals appear to survive without free water, but will use it if it is readily available.

We can, however, list some sources of the water wild animals use: Surface water from streams, pools, springs, and other forms of open or free water; snow; dew (a common source for birds and grazing animals); plant succulents (the foliage, fruits, and other parts of green and growing plants); insects and other animal life (which often contain a high percentage of moisture); and metabolic water—a few animals can create water from dry foods by converting carbohydrates into water.

The best way we have to manipulate the water supply for the benefit of wildlife is through the development, transportation, and retention of free water. We can also influence the amount of succulents by the kinds of crops we grow.

The forest-inhabitating grouse species, such as the ruffed grouse of the East and the blue grouse of the Western mountains, normally occupy areas where both succulent vegetation and free water are present. They usually are found near water, but drinking water may not be necessary to their maintenance, except possibly in late summer when feed is dry.

The sage grouse of the open and arid parts of the West apparently need water during the dry, hot summer. Then they drink surface water and tend to concentrate near streams and springs. Most of the sage grouse usually are found within a mile or so of water in summer.

The Chukar partridge has been introduced from Asia into Nevada, Washington, and other drier sections of the Western States. It prefers areas of low rainfall where surface water may be limited, but it seems to depend on free water during the dry and hot part of the year. During July and August the Chukar is usually found within a mile of water and may drink at least once a day.

Members of the quail family have some interesting differences in water requirements. The bobwhite, the most widely distributed quail in the United States, generally is not dependent on surface water, even in dry seasons, but derives all the moisture it needs from dew and succulent foods, including insects. Sometimes it does drink free water, which, however, is not essential.

The Gambel quail of the Southwest lives mostly in regions of low rainfall. It apparently can do without free water, but the largest summer populations are found near water and when water is available the Gambel quail use it during the dry seasons.

The valley quail of the Far West often lives in regions of wet winters and hot, rainless summers. During the dry months it lives near a spring, stream, or other source of drinking water. Attempts to increase the numbers of valley quail therefore must take a water supply into account.

Mourning doves and white-winged doves during the dry part of the year regularly fly to water holes or other drinking places.

The mule deer of the West and the whitetailed deer, which occurs in the East and parts of the West, seem to have similar water requirements. Indications are that both species can obtain all the moisture they need from eating green and succulent vegetation when it is available. Apparently, how-

ever, they come to water during dry and hot periods when herbaceous vegetation has matured and dried. Does and fawns particularly seek water in dry spells. The better mule deer range has available water, which the animals can use during the summer.

The pronghorn antelope also apparently must have access to free water in hot and dry times. In summer they usually range fairly close to a drinking supply and visit it each day. Antelope confined to large pastures are said to have died when they got no water, although food was ample.

The Rocky Mountain bighorn sheep lives yearlong in a well watered area. But the desert species of bighorn sheep normally do not go to water as long as green and succulent feed is available. Thereafter they frequent the seeps, springs, and water holes.

WILD ANIMALS have benefited from water facilities provided by farmers—farm ponds, the piping of springs to troughs, the impoundment of water above dams, and sumps or tanks for storing water.

The new sources of water have enabled such species as antelope and valley quail to occupy places formerly undesirable to them. But sometimes wildlife avoid them because food and cover are lacking. Quail, for instance, will not use the water if they have to leave cover and unduly expose themselves to hawks and other enemies.

Conversely, the fencing of dams, springs, wells, and adjacent areas has increased their use by wild animals because fencing and exclusion of grazing animals increased the growth of shrubs and other vegetation, that afford adequate protection.

WATER DEVELOPMENTS primarily for wildlife—springs, reservoirs, wells, and sumps or tanks, like those for livestock—are receiving more and more attention.

One is the self-filling water catchment device, or guzzler. It is a collecting apron of cement or other material, an underground storage tank, and a ramp built into the structure so animals can enter and use the water at the same level it occupies in the tank. It was designed for valley quail and has been so successful that California installed 2,000 of them for Gambel quail and, in larger sizes, for deer.

IN DEVELOPING WATER for wildlife, we need to keep in mind that water is but one of the requirements. Water alone will not lead to more quail, deer, antelope, or other desirable animals if essential parts of the food and cover are deficient or absent. If the habitat is suitable for a species, except for lack of water, making water available can be expected to lead to an increase in numbers of resident or introduced animals and their spread into unoccupied range.

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The ultimate solution to the problem of satisfying the needs of both agriculture and waterfowl for wetlands is not clearly in sight. Surely there must be room in the United States for producing ducks and the food and fiber we need. Many technical advances have increased the production of cultivated lands—to the point, indeed, of surpluses at times. But there have not been, and perhaps never can be, comparable technical advances in the production of waterfowl. They still need wetlands in the natural wet condition. No practical substitute for the natural marshes and water areas can be found. No scientific miracle can produce two ducks on wetlands that now produce one. A coordinated program of land use is the only sensible solution. A blending of the methods and opportunities I have mentioned is essential if we are to maintain our waterfowl.—THOMAS A. SCHRADER

More Wildlife From Our Marshes and Wetlands

Philip F. Allan and Wallace L. Anderson

Our marshlands are one of the least known and least valued parts of our country—yet many products and pleasures come from them.

From the small pothole the farm boy earns his first dollar from the sale of a muskrat skin. Fur bearers in coastal marshes provide a principal source of income to many families. All of the recreation from waterfowl hunting enjoyed annually by more than 2 million gunners depends on the production of ducks and geese on the inland marshes of the United States and Canada and also upon the wintering grounds along our coasts and in Latin America.

The need to manage marshes is becoming more and more urgent if the United States is to maintain or expand the production of fur bearers and waterfowl. Marshlands have been shrinking in area ever since colonial days as a result of industrial developments, urbanization, agricultural drainage and other drainage, sedimentation, and the filling and subsiding of the coastlines. Much of the marshland remaining to us cannot be used for ordinary agricultural production, and so we must find other ways to make that land economically useful.

Waterfowl and fur bearers are the principal marsh products of economic value, but many other values and products are associated with marshes. They are the homes of a vast array of interesting mammals, birds, reptiles, fish, and lesser forms of animal life. Botanists, amateur and professional, find in marshes a host of fascinating plants. Among the commercial products are alligator hides, frog legs, edible turtles, wildrice, peat, rushes and cattails, and hay.

The management of fur bearers on coastal marshes is directed mainly at production of muskrats, by far the most important of the fur producers. Marshes also yield mink, otters, nutrias, raccoons, and foxes.

In the parts of the coastal area inhabited by muskrats there is one plant that is most used by 'rats. It is the Olney bulrush, also known by the names three-cornered grass and three-square. Cattails are important to muskrats along the Atlantic coast and in the Louisiana Delta country. Two other plant species of local importance are the saltmarsh bulrush (leafy three-cornered grass or coco) in Louisiana and Texas; and paille fine (maidencane) in eastern Louisiana. Each species is found in a more or less different kind of coastal marsh.

The management of coastal marshes centers upon keeping a good stand of whichever of those plants is suitable for the site. With some plants that is easy to do, but with others management is difficult. In order to learn how to produce or maintain the kinds of vegetation you want, it is necessary to understand the conditions under which they grow best.

The principal measures that permit the management of desirable kinds of plants are controlled burning and control of water levels and salinity.

Extensive areas of marsh along the coasts are too dry or too salty to be good for production of fur bearers. They are better for cattle range and winter feeding areas for wild geese.

Fire is useful in the management of marshes when it is used with care. Unwise use of fire can do a great deal of damage. Trappers often burn marshes. Sometimes they get good results, sometimes poor. They do not always know why controlled burning is useful.

Fire is not good for any plant. In order to burn marshes properly one must know what the objective is and how to use fire to achieve it. The most important reason for burning marshes is to kill the plants that choke out the

better kinds. Then the better ones can increase. Burning, therefore, must be done in a manner that does not kill out desired kinds of plants. A less important reason for burning is to reduce accumulated dead plant materials (roughs) in order to make trapping easier and more thorough. When any burning is done it must be with knowledge of the right time of year, of the conditions suitable for the operation, and of what the end results should be.

A GOOD SYSTEM of water control benefits nearly any marsh. Ditches drain off excessive amounts of fresh or salty water. They also permit irrigation of a sort—allowing the addition of fresh or salty water—that helps the marsh operator maintain conditions favorable for the plants he wants. During dry spells ditches hold water and sustain muskrats that might otherwise leave. Muskrats use the banks of ditches for burrows and as refuges during floods. Ditches also enable trappers to move about the marsh easily and to trap it thoroughly and heavily.

Ditches in marshes should be designed to reach water sources that can be used for irrigation. A system of blocking off the sources is essential. Often the block need only be poles or stakes set at the end of the ditch. If large amounts of fresh water, or very salty water are likely to come in, carefully built gates are needed. The services of an agricultural engineer, then, will be useful.

Ditches in coastal marshes ordinarily need to be more than 2 feet deep and 4 feet wide. They are spaced 200 feet to a quarter of a mile apart. Ditches are constructed with a dragline, ditching dynamite, a marshbuggy and plow, or—in deep peat—by means of a boat equipped with choppers.

Levees are used mainly to block off unwanted fresh or salty water. They also may be constructed to impound water where the natural water level is too low. Levees usually should be 2 feet high after they have settled. The width across the top should be 10 feet and the sides should slope at a rate of 3:1. Higher levees may be needed where flooding is frequent.

If coastal marshes are used for livestock grazing and muskrat production, walkways are valuable. A walkway is a levee constructed through the marsh to permit cattle to travel into and across wet areas. The borrow pit from which soil is taken to build the walkway can be alternated from side to side of the levee to prevent excessive drainage. When a borrow pit is dug on only one side of the walkway—as along property boundaries—plugs left at intervals will prevent the formation of a ditch that will drain the land. Natural waterways are kept open by means of culverts through the walkway. Cattle can be kept from concentrating on valuable muskrat marshes by placing the borrow pit on the side of the levee next to the area to be protected and extending it well beyond either end of the area. Drift fences to keep cattle out give further protection.

Ditches and levees in coastal marshes usually cost 15 to 20 cents for each cubic yard of earth moved or about 20 to 25 cents a linear foot.

OLNEY BULRUSH GROWS BEST where soil waters are slightly salty. It will grow in water that is almost fresh—not strictly fresh—and in water that is moderately salty. Along the Atlantic coast Olney bulrush usually is found in places barely reached by monthly high tides, but where the soil is always waterlogged. Along the Gulf coast occasional storm tides are the only ones that reach areas where Olney bulrush grows. There, too, the soils are always wet—with standing water not more than 2 inches above or below ground. The soil may be peat, clay, or sand.

If a site is never burned or never grazed by livestock, little bulrush is likely to be found, because another plant—variously called marshhay cordgrass, couchgrass, or wiregrass—grows better under those conditions and chokes out the Olney bulrush.

Olney bulrush marshes should be burned every year except during droughts. Burning should begin in the South about the middle of October and be completed by mid-January. Burning is done in the North in late winter and should be finished before spring production of young muskrats is underway.

Fires should be set only when the water is standing at about an inch above ground level. Such burning tends to kill the crowns of marshhay cordgrass, but leaves the rootstocks of Olney bulrush protected. Because Olney bulrush grows best in cool weather, it recovers quickly after burning. The first burning should be limited to about two-thirds of the marsh if possible and the rest burned later. A well-placed pattern of trappers' ditches or other firebreaks helps control the extent of the burn.

It is best not to use the marshes for grazing by livestock, but if cattle are put on them, grazing should be limited to early fall and late spring. The grazing can be quite heavy at those times.

Sometimes Olney bulrush marshes receive too much salty water. "Scalds" may appear—areas temporarily bare of living plants. When the increase of saltiness is slow, plant life gradually changes—smooth cordgrass (seacane, oystergrass), seashore saltgrass, and needlegrass rush (black rush, paille chat tigre) increase. The first step in correcting the condition is to cut off the source of salty water. That may be done by blocking waterways that lead into the marsh, or, if that cannot be done, by constructing levees to keep out salty water. In extreme cases, water-control structures may be required that drain salty water and hold back fresh water.

Where soil water is too fresh, Olney bulrush grows poorly. An increase in cattails, sawgrass, cutgrass, or arrowheads usually indicates too much fresh water. The condition occurs where drainage waters from upland areas are dumped on the marshes or where natural drainage is so poor that fresh water accumulates. It can usually be corrected by cutting ditches to a source of salty water. In places where highways, levees, or other obstructions tend to pond fresh water, cuts or culverts are needed to aid in drainage. The blocking or diversion of fresh water sources might be required in unusual situations. Good drainage is important in deep peat marshes, for the marsh stays firm and more suitable for Olney bulrush. Drainage also is needed in order to make the marsh firm if muskrats or wild geese overgraze it. Trappers refer to such situations as eat-outs.

Although it often can be done, it seldom pays to convert a large fresh marsh or a large salt marsh to the medium conditions required by Olney bulrush.

Cattails grow best where the soil water is very fresh, but some will grow in moderately salty water. These plants occur where water depths range from ground level to about 2 feet above ground level. They thrive on either mineral or peat soils. Other plants, such as the large-stemmed bulrushes, giant cutgrass, arrowheads, and sawgrasses sometimes grow in the same places, but only the sawgrasses seriously compete with cattails—and then generally on deep peat soils.

On the deep, fresh coastal marshes suitable for their growth, cattails usually crowd out other plants. Little special management is needed for them unless they are being destroyed by fire, livestock, or salt scalding. Along the gulf coast, Jamaica sawgrass may require control in cattail marshes. A strong burn on a sawgrass area during a dry season, and especially before a gulf storm, may destroy the sawgrass. If moderately salty water can be run into sawgrass areas long enough to scald the plants—and then be cut off—conversion of the vegetation to more desirable kinds can be achieved.

Cattail marshes along most of the gulf coast are poor muskrat-producing areas, though they do produce nutrias. On the Atlantic coast, however, these

marshes yield valuable crops of muskrats. The most important management measures are protection from livestock, prevention of overgrazing by muskrats, and installation of level or blind ditches. Burning is used occasionally to remove dead plant materials, but should only be done when water covers the root crowns of the cattails.

Cattail marshes seldom require water-control measures unless other plants begin to replace the cattails. Invasions of cordgrasses, common reed, and other salt-tolerant plants mean that the site is becoming too saline. The sources of salty water then must be blocked, or the marsh must be leveed to impound fresh water. The replacement of the cattails by panic grasses, giant cutgrass, or shrubs means that the site is becoming too dry. Plugging drainageways, building levees, or flooding with fresh water are means of preserving cattails on drying marshes.

Saltmarsh bulrush grows on peaty soils where soil water is quite salty. It thrives where soils are wet, but does not require standing water. Along the Atlantic coast the plant is relatively unimportant, but along the Gulf, saltmarsh bulrush areas produce many muskrats.

In most respects muskrat management on saltmarsh bulrush areas is similar to that on Olney bulrush marshes. Burning to control marshhay cordgrass is done in the same way, but it is done after the middle of February in the South, and 2 to 3 weeks after plant growth starts in the North. This bulrush makes its best growth in the spring.

Increasing saltiness of soil water is not of much concern on saltmarsh bulrush areas. Increases in water depth may cause invasion of smooth cordgrass—a fair muskrat food plant. Drying marshes may be invaded by big cordgrass, common reed, bigleaf sumpweed, eastern baccharis, or by gulf cordgrass in Louisiana and Texas. The appearance of those plants means that more water must be held on the marsh.

Paille fine is a fresh-marsh grass easily killed out by salty water. In eastern Louisiana, paille fine marshes are important muskrat producers. The grass grows well on mineral soil but grows best on floating peat, known locally as flotant. When paille fine is heavily grazed by livestock or burned, it may be replaced by less desirable plants. It will not thrive in water more than a few inches over the root crown. It will not live in soil that is not wet.

Little is known about how to manage paille fine marshes. The grass provides good livestock forage and is used widely for that purpose. When such marshes are used for muskrat production, the two principal management measures needed are the prevention of overgrazing by muskrats and careful control of fire—especially during dry periods. Salty water should be prevented from covering the marshes, if possible. The permanent flooding of paille fine marshes on mineral soils by fresh water to depths of 4 inches or more will kill out the grass.

The management of plants and manipulation of water provides the main permanent features of muskrat production. State biologists in a number of localities have found that control of raccoons when they are unusually abundant results in better muskrat crops. Muskrats should be trapped heavily during years of abundance—and lightly, if at all, during periods of scarcity.

Management of waterfowl on coastal marshes hinges principally on increasing areas of open water and developing and maintaining desirable kinds of plants. Contrary to general opinion, coastal marshes densely covered with undisturbed marsh plants are not of great value to waterfowl. Lagoons, bays, potholes, and streams within the marshes make up the greater part of the area frequented by ducks and geese. When the densely covered marsh sites have been flooded, burned,

or heavily grazed, however, they often become better places for waterfowl.

Along the Atlantic and gulf coasts there are hundreds of thousands of acres of marshland which have no foreseeable use for producing crops or livestock forage but which can be devoted to waterfowl habitat and developed for that purpose.

Open-water areas are created in marshes mainly by impounding, blocking drainageways, or burning areas of deep peat. Most of the coastal waterfowl refuges and many of the private hunting clubs have demonstrated the success of impounding water as a means of developing duck marshes. The ideal impoundment is one on which water can be carefully controlled. The best control structures keep out high water—either salty or fresh—when unwanted, permit rather complete drainage, and hold 6 to 18 inches of water when needed. Such impoundments are expensive and ordinarily call for experienced engineering aid. In rice-growing areas, impoundments may serve the dual purpose of storing drainage water during the waterfowl wintering season and serving as a source of irrigation water in summer.

Marshes may be partly flooded by blocking natural drainageways with floodgates or other barriers. The removal of obstructions to water flow and the diversion of drainage water into suitable marshes also are means of flooding.

Areas of deep peat often become good waterfowl grounds when fire burns out holes. Such burns are made when marshes are usually dry. There are serious hazards in deep burning of marshes because of the difficulty of keeping fires within bounds of the area to be improved.

Among the chief benefits of flooding is the destruction of tall, dense growths of plants that have little value for waterfowl and their replacement by better species. On marshes where water can be controlled, removal of water during the growing season permits light cultivation of the valuable plants to increase production or the planting of such species if they are not already present.

Some alteration of the vegetation is necessary on nearly every coastal marsh in order to have satisfactory conditions for waterfowl. More severe treatments are required than on muskrat marshes. Where grazing can be done on the marsh, livestock help produce conditions favorable for water fowl. Very heavy grazing in the spring—to the point where most of the taller and ranker plants are killed out—results in an increase in more desirable plants. Marshes in which geese are hunted are improved by this method.

Where marshes cannot be grazed, they often may be improved by controlled burning. Burning marshes for waterfowl differs from that for fur bearers. The burn needs to be hotter and more complete. It is best done in the spring or early summer. Water levels should be at or slightly below ground surface.

Coastal marshes seldom need planting in order to produce good conditions for waterfowl. So many kinds of plants ordinarily are present that it is only necessary to create favorable conditions to have ample stands. All that needs to be known about such management, however, is not known, except the principle of reducing competition from the less valuable species. That can be done by the methods we have described.

Planting may be useful in places where the soil is relatively bare, dry enough to be lightly tilled, and moist enough for seeds to sprout. The surest plants to grow from seed are smartweeds, barnyard grass, and millets, which can be broadcast at 15 to 30 pounds of seed an acre and lightly harrowed. If conditions are suitable for drilling the seeds, the rate of seeding can be reduced one-third. Federal law prohibits the planting of cultivated plant species such as corn, wheat, and rice for the purpose of attracting waterfowl to shooting grounds.

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Common plants of the coastal marshes that have high value as food for the waterfowl include pondweeds, wildcelery, wigeongrass, smartweeds, watershield, waterlilies, the spikesedges, naiads, and beakrushes. Some bulrushes also are valuable. Plants of low value to waterfowl, which often grow in abundance, are common reed, cordgrasses, cattails, giant cutgrass, rushes, saltgrass, sumpweed, alligatorweed, coontail, and waterhyacinth.

The arrowheads and sawgrasses provide seeds that ducks like, but the plants often grow in stands too dense to provide good duck marsh.

On inland marshes production of muskrats is far more important, economically, than production of mink or raccoons.

Muskrats are better able to convert marsh vegetation into a useful product than are hogs, cattle, or sheep. The fur produced by muskrats will be more valuable than the small amount of meat or milk that might be produced by grazing domestic livestock. Furthermore, grazing animals are less likely to contract diseases and parasites if they are excluded from marshes.

The best plants for muskrats on inland marshes are cattails, arrowheads or duckpotato, burreeds, bulrushes, and sweetflag. All will grow in marshes that have water levels at or near the surface of the ground to as much as 2 feet above the surface.

Many marshes have many muskrat food plants but have such shallow water that the foods are not available to the muskrats in the winter when the marshes are frozen solid. The muskrats then are forced to move out in search of something to eat and most of them are lost to predators.

Marshes used for the production of muskrats should not be grazed. The hooves of grazing animals often break through the thin layer of soil between the ground surface and the muskrat den. Then the muskrats have to construct new dens. Too much construction is particularly troublesome along level ditches, because each new den adds more sediment to the bottom of the ditch and hastens the time when a clean-out will be needed.

Fire is seldom used on inland marshes. It may be used occasionally to eliminate woody plants that have invaded the marsh during a series of dry years. In that situation, however, better results usually are had by cutting or bulldozing the woody plants during the winter or by using herbicides during the growing season.

Fire may be used in unditched marshes to eliminate accumulations of dead vegetation that hinder trapping operations. It should be used for that purpose only when needed and only when the water level is high enough to protect the plant crowns and rootstalks.

Level ditching is an effective and economical practice in shallow marshes.

The Wisconsin Conservation Department, in research conducted on Horicon Marsh between 1949 and 1953, tested ditch spacings of 50, 100, 200, and 400 feet. They determined that ditches placed at 200-foot intervals produced the most return when investment and muskrat production are considered together.

A 10-acre plot ditched at the 200-foot spacing produced 554 muskrats in the 5-year period of the experiment. That is an average yearly harvest of 11.1 muskrats an acre and 23.8 muskrats for each 100 dollars invested in ditching.

An economic analysis, based on the muskrat production attained with the 200-foot spacing and using an average value of 1 dollar and 47 cents a pelt and 10 cents a carcass, indicates a yearly net return of 12.68 dollars an acre after expenses for labor, equipment, depreciation, taxes, maintenance, and interest on investment have been deducted. The gross annual income an acre was 17.43 dollars. Net income plus labor income was 14.51 dollars an acre a year. The initial investment for level ditching was 46.50

dollars an acre. The rate of interest earned on the capital investment was 31.2 percent.

Level ditches have no grade and need not have an outlet. They do not drain the marsh; they simply create deeper water, which makes food available to muskrats during winter. The spoil banks also provide denning sites and offer some degree of safety from drowning during floods.

Construction of level ditches is feasible in peat or muck or in medium to heavy mineral soils. Ditching is not recommended in places where light, sandy soils will be encountered. Ditches should be 5 to 6 feet deep in the North, 4 to 5 feet deep in the Central States, and 3 to 4 feet deep in the South.

Level ditches should be 12 to 20 feet wide. The spoil banks should be 3 to 4 feet high and placed on alternate sides of the ditch at 50-foot intervals. A berm approximately 6 feet wide between the edge of the ditch and the edge of the spoil bank will prevent the weight of the spoil bank from caving in the side of the ditch bank.

A dragline is the most satisfactory type of equipment to use in constructing level ditches. Blasting has been tried, but it costs no less than dragline construction and the desired depth is hard to obtain. Blasting does not produce the spoil banks that are important in providing denning sites for muskrats.

Long, straight ditches should be avoided because winds blowing lengthwise in the ditches may create waves that will make handling a boat difficult. Wave action may also cause erosion and sedimentation. Changing direction by means of a zigzag pattern at 200-foot intervals is recommended.

Trapping in level ditches is relatively easy. Sets are made from a boat and the need for trudging through heavy marsh vegetation is eliminated.

Control of water levels often provides the most economical methods of improving inland marshes for muskrats, but this method is limited to marshes having a reliable water supply such as a stream or heavy-flowing spring.

Control of water levels usually requires the construction of earth dikes at the outlet of the marsh and at such points as may be necessary to protect adjacent farmland from flooding when water levels are raised in the marsh. Also required is some type of structure, usually concrete or creosoted wood, that will allow water levels in the marsh to be varied from 6 inches to 2 or 3 feet above the ground surface.

Water levels should be maintained at about 6 inches during the growing season to provide the best growing conditions for food plants for muskrats. At the time muskrats begin to construct houses, water levels should be raised gradually to 3 feet in the North, 2 feet in the Central States, and to 1 foot in localities where freezing seldom occurs.

Raising water levels in the fall and maintaining the raised level throughout the winter are necessary to prevent the marsh from freezing solidly and to make sure that muskrats will be able to get food at all times.

Waterfowl production on inland marshes is important in maintaining the supply of this valuable resource. Waterfowl production on farmland is almost always a product of water areas not suitable for other uses or is a byproduct of wetlands managed primarily for muskrats, livestock water, or water storage. Because of the migratory nature of waterfowl, it is generally economical for farmers to manage marshes primarily for waterfowl only if they are able to sell shooting rights.

Level ditching is not recommended primarily for waterfowl production but waterfowl production is increased by the practice.

Research by the Wisconsin Conservation Department at Horicon marsh in 1952 and 1953 revealed that the spoil banks of level ditches on 35 acres had 24 waterfowl nests in 1952 and 51 nests in 1953. Nesting success was 46 percent in 1952 and 20 percent in 1953.

Predators, principally raccoons, were believed to be responsible for the relatively low nesting success. The research indicates that level ditching concentrates both waterfowl and predators on a relatively small area, and that rather thorough control of predators is necessary for high nesting success.

Control of water levels can help increase waterfowl production on inland marshes if a dependable water supply exists. There are two methods of management.

The one most likely to result in the highest production of waterfowl is to maintain a uniform depth of 18 to 30 inches of water throughout the year. Such management favors the growth of pondweeds, wildcelery, coontail, duckweeds, musk grass, and duckpotato. It also furnishes courtship areas in the spring and may provide a brood area in the summer.

Another method is to draw the water down in the spring so that a saturated soil condition is maintained during the growing season. The soil should be wet, but there should be a minimum of water on the surface. Such management will favor the growth of smartweeds, wild millet, and burreeds. The water level should be raised to 18 inches in the fall to make the foods available to waterfowl. The method is not likely to encourage waterfowl nesting or the production of muskrats. It is primarily valuable in producing good waterfowl shooting.

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Waterfowl and the Potholes of the North Central States

Thomas A. Schrader

The prairie pothole region in Minnesota and the Dakotas, the most important nesting area of waterfowl in the United States, may have produced 15 million ducks a year in the past. Today it produces about 5 million. Drainage is mainly to blame for the difference.

Nature made the region ideal for nesting waterfowl. It is dotted with many shallow depressions—potholes, sloughs, marshes—which hold water for a few weeks in early spring or all summer long. The potholes are of all shapes and sizes. Some cover 100 acres or more, but most of them cover less than 10 acres.

We hear of the days when flights of ducks and geese darkened the sky, so numerous were they, in their spring and fall migrations between wintering grounds in the South and summer nesting areas in the North. But no more. The alarming decline in numbers of waterfowl came when farming brought drainage of the wetland areas and destroyed more than half of the nesting range of ducks in the prairie pothole region. The additional corn and wheat produced as a result of the drainage can be recorded as a gain in the dollar-and-cents ledger; but the change has left us poorer in the waterfowl resource account, which is kept in a different set of books.

In calculating the value of further drainage, two other factors should be considered. First, since the most economically drainable land has been drained, any future drainage is likely to be more difficult and less rewarding. Second, with increasing demand and decreasing supply, the duck has become vastly more valuable. In pioneer days the value of a duck was expressed in cents per pound, but today waterfowl values do not find true expression

behind a dollar sign. They have recreational, social, and cultural values which make their meat values appear almost inconsequential.

It might be argued that we could get along without ducks because a relatively small part of the population is interested in this resource. That reasoning, however, would just as logically lead us to argue that America might also get along without symphony orchestras, zoos, national parks, wilderness areas, and many other features that are used or appreciated by a relatively small proportion of the population. The very fact of their existence indicates that we in America recognize the need for more than bread alone.

Because of the importance of migratory waterfowl, our Government has assumed a statutory obligation to protect and enhance this resource through treaties with Mexico and Canada. Recognizing the value of the resource, both economically and culturally, and being aware of the importance of our legal obligations to protect migratory waterfowl, conservationists are deeply concerned over the effect of further exploitation of wetlands in the United States, upon which waterfowl depend for existence.

DRAINAGE in the prairie pothole country is of particular concern because the area lies within the nesting range of many species of waterfowl, and any loss in the area is a loss of critically needed habitat for breeding. The prairie pothole country is in North Dakota, South Dakota, Minnesota, and Iowa. It was first farmed after the Civil War. Between 1870 and 1930 practically all of the wetlands of Iowa, the southern tiers of counties in Minnesota, and the Red River Valley in North Dakota and Minnesota were drained. Their deep, level soils gave them the greatest potential for farming.

The trend in land-use development was reversed during the 1930's. Millions of acres of land throughout the Midwest were removed from production in the attempts to reduce crop surpluses. At the same time the severest drought in 100 years made water one of the most precious resources of the region. Drainage ceased almost entirely, and the State and Federal Governments spent millions of dollars to conserve water. The Fish and Wildlife Service and many of the State conservation departments acquired many drainage enterprises in order to plug the drainage ditches, conserve water, and restore marsh habitat for waterfowl and fur-bearing animals.

Those who participated in the water-conservation programs of the 1930's were appalled to discover shortly after the end of the Second World War that drainage was again assuming important proportions in a region where, such a short time before, water was considered so precious.

It soon became evident that drainage was snowballing. Under the impetus of high farm prices and Federal subsidies, there was a natural incentive to put every acre into crops, and new drainage ditches appeared in great numbers throughout the pothole country.

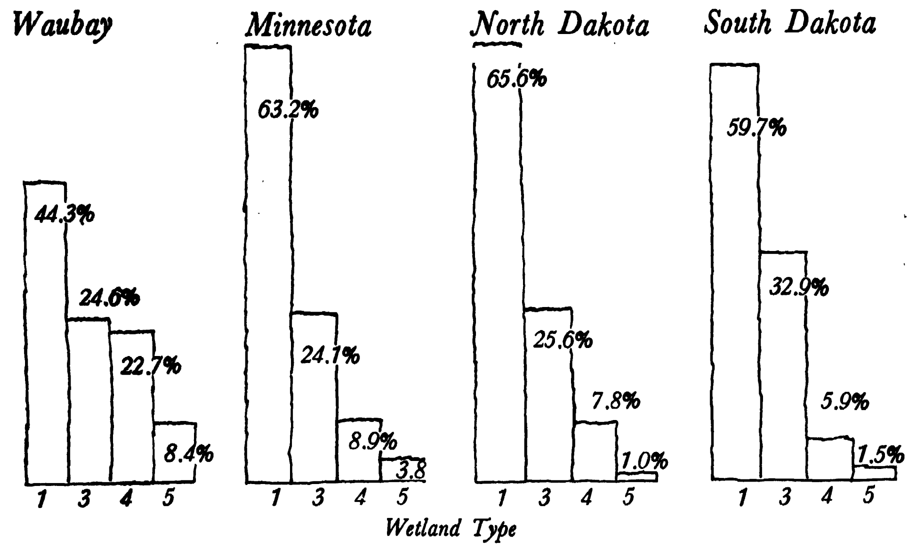
Preliminary examinations by the Fish and Wildlife Service, of the Department of the Interior, in 1948 and 1949 established three salient facts about drainage in the prairie pothole country:

1. Drainage was a widespread and growing agricultural practice subsidized by the Federal Government, with little regard for its effect upon waterfowl, fur bearers, shore birds, and other wildlife.

2. This region was generally considered very important for waterfowl production, but there was much yet to be learned about the specific value of various types of small water areas to waterfowl and other wildlife.

3. The agricultural agencies, in most cases, maintained that the drainage being done under their supervision was either beneficial or neutral in its effect upon wildlife.

Because of the seriousness of the



Relative abundance of Wetland Types.

situation, the Fish and Wildlife Service initiated a study of waterfowl conditions in the prairie pothole region.

THE STUDY was designed to determine the importance of the pothole country to continental waterfowl production, the use that waterfowl made of the various types of water areas, the distribution and number of water areas in the region, and the rate at which the water areas were being drained.

It was hoped that, if the study showed that this waterfowl-production area was worth saving, ways could be found to encourage landowners to preserve their wetlands.

Originally, the prairie pothole region covered about 115,000 square miles. Drainage has eliminated more than half of the waterfowl habitat, and today there remain about 56,000 square miles in North Dakota, South Dakota, and Minnesota that contribute significantly to waterfowl production.

The soils of the area are either Chestnut, Chernozem, or Prairie soils, which have been devoted to row crops, small grains, hay, and pasture.

Throughout the area, glaciation has deposited parent materials of varying thickness. The topography ranges from flat river valleys to steep moraines. In the morainic areas natural drainage has not become well established, and is here that lakes and potholes are most numerous.

Average July temperatures range from 66° in northwestern North Dakota to 72° in southeastern South Dakota and southwestern Minnesota. Annual precipitation averages 16 inches for most of western North Dakota and 24 inches or more for eastern South Dakota and western Minnesota. Soils are high in fertility. In the rolling pothole country, they are shallow and easily eroded. Erosion and insufficient moisture are the major agricultural problems.

THE NUMBER OF water areas in the pothole country varies from day to day. Aerial surveys conducted by the States with Federal Aid in Wildlife Restoration Funds have given valuable information on the abundance and distribution of water areas in the spring. The surveys showed for North

Dakota approximately 664,000 potholes, covering 2,152,000 acres; for South Dakota, 422,000 potholes, covering 817,000 acres; and for southern and western Minnesota, 124,000 potholes, covering 1,464,000 acres—a total of 1,210,000 potholes, covering 4,450,000 acres.

Their number and acreage vary considerably through the year as a result of natural water losses or heavy rains. In North Dakota the 664,000 bodies of water present in spring had dropped to 269,000 by late summer, a 59-percent reduction—from more than 9 potholes to the square mile in spring to fewer than 4 in the fall.

Potholes are not scattered uniformly, but vary from a few to more than 150 to a square mile. Regardless of the number to the square mile, it is the association or community of potholes in this fertile area that makes it the best waterfowl-producing region in the United States.

Studies of the amount of drainage in the pothole country were conducted in 1950 and 1951. The results confirmed fears that drainage was widespread and was significantly reducing the number of water areas there. On a 19-township sample in west central Minnesota containing 14.2 potholes to the square mile, 2.75 potholes the square mile were drained between 1945 and 1950. This amounted to drainage of 16 percent of the water areas during the 5-year period. On a study area in South Dakota, 11 percent of the original wet acreage had been drained by 1950.

In the 3 States, on the basis of drainage data reported in records of the Production and Marketing Administration, some 64,000 potholes, of an aggregate area of 188,000 acres, were drained in 1949 and 1950. Since some drainage was done besides that assisted with subsidy payments, the total amount was greater. More than 2 percent of the remaining wetlands in the three States have been drained annually in recent years. If this trend continues, all wetlands in the prairie pothole country could be eliminated in 30 to 50 years. All potholes cannot be economically drained, but enough can be drained to cripple, if not eliminate, waterfowl production there.

The importance of potholes to waterfowl was studied intensively during the 4 years of investigation. With the knowledge that more than a million potholes existed in the region, it was necessary to determine what use waterfowl made of them. Much of the research was carried out on an 11-square-mile study area near Waubay, in Day County, South Dakota. The Waubay locality is typical of much of the pothole country in North Dakota and South Dakota. Much of the land is steeply rolling. The soils are relatively light and often stony. Farm crops are primarily small grain, with some hay and pasture. On the area are at least 390 water-holding depressions covering 1,055 acres. The potholes vary considerably in size, depth, and vegetation.

Waterfowl make different use of water areas of different characteristics. The wetlands of the pothole country were classified according to a system set up by a wetlands-classification committee of the Fish and Wildlife Service, and the following types were found:

1a. Intermittent areas. Shallow depressions that contain standing water for only a few days in a wet spring or after heavy rains and are generally not more than 20 inches deep at any time. They are always dry by June 1, and in many years they are dry throughout the season. Few ever have any effect on crop production except to delay seeding in years of heavy runoff.

1b. Temporary marshes. Shallow depressions that usually contain water for a few weeks in the spring and after heavy rains. They may hold water through June and into July in years of heavy runoff. They may hold up to 24 inches of water in the spring of a year with heavy runoff or may be com-

pletely dry after an open winter. In dry or moderate years, crops may be raised in these areas, but in wet years they are flooded too long for cultivation.

3. Shallow marshes. Commonly contain up to 30 inches of water in the spring and will hold water through July of a wet year. A few such areas hold no water in years with below-normal precipitation. They are all too wet to cultivate in years with near-normal runoff.

4. Deep marshes. These areas hold up to 48 inches of water in a wet spring and often hold water all year. In dry years, most of them go dry sometime during the summer, but almost always have some water in the spring. Most are overgrown with emergent aquatic vegetation.

5. Open water. Contain up to 60 inches or more of water in a wet spring and must be able to hold at least 36 inches without overflowing either over land or into a permeable underground channel. These areas may have a ring of marginal vegetation.

DURING THE SPRING when the ducks pair off to breed, their major requirement is space to maintain a degree of isolation from other ducks of the same species. As the space required by a courting pair need not include a large acreage of water, more pairs can be accommodated at this season by a large number of small, temporary water areas than by a small number of large ones. The small temporary areas and shallow marshes (1a, 1b, and 3) may be considered "territorial waters" for ducks in the courting season. The larger deep marshes and open-water areas (4 and 5) are also used, but they have greater value in supporting broods later in the season. In the spring, a courting pair of ducks usually take up residence in a locality that includes a number of potholes and will make use of several of them, staying within a fairly well-defined area of probably less than a square mile. These territories overlap, but the number of pairs of a single species that will use an area is determined by the number of courting sites available.

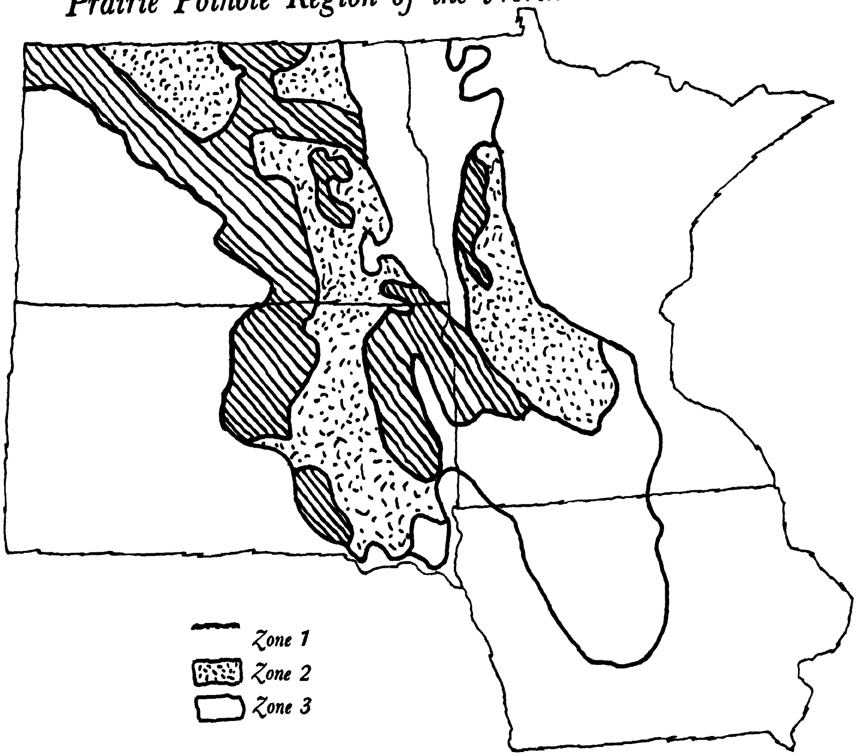
THE HEN'S CHOICE of a nest location seems to be influenced by a desire for isolation. Most of the nests in the pothole country are on dry land, occasionally a considerable distonce from water. The important factor in choice of a nest site seems to be suitable cover. Some nests are built over water, generally in the deep-marsh or open-water areas (4 and 5), where there are dense stands of hardstem bulrush and cattail.

During the brood-rearing period, young ducks are flightless and vulnerable to predators. In some potholes the vegetation, if not too dense, serves as escape cover from enemies. Escape by diving may be offered in open-water areas by water at least 20 inches deep. The best rearing conditions for broods are usually found in deep potholes of medium size and mainly of open water, but surrounded by a margin of rather sparse emergent vegetation. Such conditions are most often found in deep-marsh or open-water potholes (4 and 5) of 2 to 10 acres. Permanent lakes too large to be considered potholes generally are so windswept as to be of only moderate value for broods.

Ducks move about a lot throughout the breeding season. Pairs are able to adapt themselves to varying conditions created by drying or refilling of potholes and use any suitable sites within or near their breeding territory. Flightless broods also move readily from pothole to pothole in response to changing conditions. They will travel more than 2 miles to more desirable areas.

In the spring, when the greatest need is for space, the small temporary areas hold water, thus allowing the breeding population to spread out. After the young have hatched, most of the temporary waters have dried out, leaving the larger, more permanent areas. Then the space requirements of ducks are no longer a limiting factor, and needs are amply provided by the brood areas.

Prairie Pothole Region of the North Central States



Zone 1: Rolling to rough terrain, soils fertile but shallow and very susceptible to erosion by wind and water, potholes numerous, duck production very high, drainage heavy in the eastern cultivated area and light in the western range land.

Zone 2: Level to rolling terrain, soils fertile and of moderate to shallow depth, erosion severe to moderate, potholes and marshes quite numerous, high to moderate duck production, and much drainage in progress.

Zone 3: Level terrain, soils fertile and deep, erosion seldom a problem, a few large marshes remain, duck production low except on remaining marshes, and drainage has already removed most of the once numerous wetlands.

Maximum production of waterfowl in the pothole country results from the interrelations of a number of different types of pothole, each fulfilling certain needs. An isolated temporary pothole not near a more permanent pothole has no value because it furnishes no brood habitat and can satisfy only the courtship needs of the birds. On the other hand, a permanent pothole by itself, while ideal for broods, is of limited value because only a few courting pairs will use it. Only when it is surrounded by a number of temporary waters will its maximum carrying capacity for broods be realized. The waterfowl habitat of the pothole region therefore can be evaluated only on the basis of the entire community of potholes and surrounding lands, rather than of individual water units.

THIS COMMUNITY RELATIONSHIP has been determined for the Waubay area and for other representative samples in the three States. The graph on page 598 shows, by number of potholes, the comparative abundance of the four

wetland types involved. It will be noted that the community relationship is essentially the same for all four samples with from 44 to 65 percent temporary areas, 24 to 32 percent shallow marshes, 6 to 22 percent deep marshes, and 1 to 8 percent open water.

In the Waubay area, with an average of 35 potholes to the square mile, the 4-year average annual production was 140 ducks the square mile. There are variations in the number of potholes and in the community relationships of other areas, so the figure of 140 ducks for Waubay may not apply to the pothole country generally. Other studies have shown that 3 of the 4 ducks produced in the United States are produced in Minnesota, North Dakota, South Dakota, and Montana. Most of them are produced on pothole-type habitat.

CONTINUED HIGH PRODUCTION from the prairie potholes is essential to the future of waterfowl hunting throughout the Mississippi and Central Flyways. The ducks produced here are also of major importance to hunters outside those Flyways.

Band returns from 2,063 mallards, gadwalls, and pintails, banded in June, July, and August within the general pothole region of the United States, show that the ducks were shot in 39 States, Alaska, Canada, Central America, and South America. Of redheads banded in the pothole region during the same months and recovered away from the immediate banding area, 13.5 percent were taken in the Atlantic Flyway. Of the pintails recovered away from the immediate banding area, 19.2 percent were shot in the Pacific and Atlantic Flyways in the United States and in Alaska and British Columbia. Prairie pothole ducks thus contribute to waterfowl hunting in most parts of the United States.

DESPITE CLAIMS that the drainage of temporary potholes into more permanent ones has improved the remaining areas for broods, we have been unable to find such benefit. There is no clearly defined type of pothole that can be drained without damage to the total waterfowl habitat.

A program to save these wetlands is imperative if the Federal Government is to live up to its obligations.

While the Fish and Wildlife Service should take the lead in developing a program to save the wetlands, the statutory obligation to do so extends to other Federal departments. Because waterfowl are as much a product of the soil as are grains, livestock, or timber, and because the prairie pothole country is almost entirely private farmland, it appears that the job of saving the wetlands should be shared by the landowners and by the Department of Agriculture. The landowners are the ones who actually have the fate of the potholes in their hands. Since the Department of Agriculture works most closely with the farmers, its agencies are in a good position to cooperate in a program to save the wetlands.

Landowners may practice drainage for a number of reasons. Two seem to be most important—the normal desire to increase farm income and the wish to get rid of scattered, nuisance potholes, which sometimes hinder farming.

AN ACCEPTABLE PROGRAM to save the wetlands must consider the two factors. In general, plans for saving potholes must strive to offer alternatives that will give the farmer an income approximately equal to the net income that can be achieved by drainage. The farmer also might need compensation for the trouble an undrained pothole causes.

The suggestion is often made that public agencies buy the areas that are needed to maintain the continental waterfowl population. The suggestion has merit, because purchase of the lands insures that they will never be drained, and the private owner is relieved of paying taxes on the land he considers unproductive. At best, however, public acquisition or lease of wetlands can provide only a fraction of the total habitat needed. Public

acquisition will be costly and difficult. Even if adequate funds were available to public agencies for the purpose (which they are not), this approach, if it were the only one, has a number of limitations.

PUBLIC PURCHASE will be the most important method of saving the remaining wetlands in zone 3 of the pothole region. There a considerable number of valuable marshes remain; we fear they will be drained if they are not brought into public ownership. As part of a well-planned program to manage upland game, for animals, and waterfowl, the Minnesota Game and Fish Division has made notable progress in acquiring wet areas in Minnesota.

Many marshes in zone 2 can be saved only through public acquisition, but it may be necessary there to lease rather than buy many potholes because they are so small and widely scattered that purchase would be difficult and costly.

Potholes in zone 1 are so numerous and so widely scattered, and the area is so large that an acquisition program would seem to have little chance of success. Some wetlands will be bought by public agencies, but most will have to be preserved for waterfowl management in some other way.

Because more public shooting areas are needed to remove pressure from privately owned lands where most of the hunting is now being done, a buying and leasing program could carry the additional benefit of providing public shooting grounds. A program of lease and purchase of wetlands is entirely a responsibility of the State game and fish departments and the Fish and Wildlife Service. The agricultural agencies can help by pointing out suitable places for prospective purchase.

A SECOND METHOD of saving wetlands is also a responsibility of the fish and wildlife conservation agencies, but there appear to be opportunities for the agricultural interests to share in the job. That involves developing alternative uses for the wetlands, which take waterfowl management into account and will increase the farmers' income from the wetlands. A few of the opportunities bear mention.

Many potholes hold water for such short periods that regular crops are grown in them without drainage, and landowners should be encouraged to crop such areas. Even some places that retain water somewhat longer can be used for moist-soil forage crops—reed canarygrass, whitetop, and tall wheatgrass, among them. Several other species appear to have good possibilities for moist-soil culture, and further research may reveal additional ones with better growth characteristics and higher protein values than those mentioned.

Another possibility is to use the deep-marsh and open-water areas as a source of water supply for farm uses. Fencing or water-control works may be required in some places. A larger and more dependable supply of water would be made available for livestock and perhaps for irrigation. The supply should not be overappropriated, however, and the pothole pumped dry.

The use of potholes for producing fur crops and minnows and for duck hunting might give the owner of wetlands additional income.

Returns from such alternative uses might indeed exceed the net income a farmer would get by drainage and conventional cropping. The Fish and Wildlife Service, recognizing the possibilities of such an approach, has assigned biologists to work with units of the Department of Agriculture and with farmers in arousing wider interest in the needs and possible solutions.

A THIRD METHOD—perhaps the most promising from the standpoint of waterfowl management—involves a reconsideration of land use in the pothole region. Zones 1 and 2, as shown on the map, have the most potholes. Most of the many potholes in zone 3 were drained because the land is level

and fertile. The soil in zones 1 and 2 is shallow, and much of the land is rolling or hilly.

Some agricultural authorities believe that row-crop and small-grain farming is not the best use for much of the land in the two zones. They recommend that the land be used primarily for grass and cover crops.

Such a shift could result in less drainage in the future, might raise the economic level of the landowner, and protect our waterfowl resources. The development of a farm program in the rolling, shallow-soil country that would plan for and expedite such a shift to grassland farming would contribute to good waterfowl conditions.

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Wetlands and the Management of Waterfowl

Samuel P. Shaw and Walter F. Crissey

Ducks and geese are crops of the land in much the same sense as wheat and corn.

Agriculture and waterfowl-management programs often compete for land on which to grow the crops. Millions of acres of prime waterfowl habitat have changed from waterfowl wetlands to agricultural drylands—mainly through flood-control and drainage projects. This reduction in living space for waterfowl has resulted in a corresponding reduction in their continental populations.

Whether waterfowl continue to decline in the future depends largely on the extent to which projects to reclaim the wetlands consider the living-space requirements of these birds. Wetlands also furnish living space for dozens of resident game animals—notably the muskrat—but this chapter is confined to the importance of wetlands to migratory game birds, particularly ducks and geese.

From the sportsman's point of view, waterfowl are a natural resource well worth maintaining. Duck hunters have doubled their ranks in the past decade. They now number about 2 million individuals who annually enjoy at least 10 million days afield. They spend more than 100 million dollars a year for such items as food, lodging, travel, and equipment. Additional millions of Americans find recreation in observing and photographing the birds in their wild environs. In view of the demand for recreational facilities and the amount supplied by the waterfowl resource, maintenance of migratory-bird populations deserves high priority in future planning for land use.

Keeping the waterfowl business solvent is primarily the responsibility of the Federal Government. That is as it

should be, because ducks and geese migrate without respect to State and national boundaries. They travel annually from the northern part of the continent to the southern part and return. The problem of managing the resource, therefore, is international in scope.

Water areas used by waterfowl are of two categories—permanent water bodies and the so-called wetlands. Permanent waters are a necessary part of waterfowl habitat, but because the lakes, reservoirs, streams, and deeper coastal waters can be depended on to remain fairly constant in extent and may even increase in number and acreage in the future, their preservation for the use of waterfowl is not an immediate problem in waterfowl management. The protection of those areas from pollution and other influences detrimental to their ability to support waterfowl is, of course, another matter.

We shall deal here primarily with habitat represented by the wetlands of the Nation—the waterlogged or shallow-water lands given such names as meadows, marshes, sloughs, potholes. swamps, bogs, overflow lands, and shallow ponds. Potentially, most wetlands can be drained, diked, or filled, and converted to dry-land uses. Wetland habitat, as opposed to permanent open water, furnishes breeding sites for most of the North American ducks and geese and contributes an important part of the habitat used during migration and wintering. Wetlands, therefore, are a primary requirement of waterfowl.

A WETLANDS SURVEY showing the extent, location, type, and value of wetlands for waterfowl was undertaken by the United States Fish and Wildlife Service in cooperation with the conservation departments of the States. The first phase of the job was completed in June 1954. Some of the results are presented here. The main purpose of this stocktaking of wetlands was to show the relative importance to waterfowl of the wetlands remaining in each State.

In determining the extent of wetland areas available for waterfowl use, all of the significant areas in some States were included in the inventory; in other States, because the use was restricted largely to certain well-defined physiographic regions, only part of the total wetland was included. In all instances, however, no extensive wetland areas of real importance were overlooked. Nationwide, this inventory cataloged an estimated 90 percent or better of each State's important waterfowl wetlands.

All areas were measured in acres and plotted on county and State maps. The detailed acreage tables and maps are available for review by any public agency or private conservation group that can make use of them. More general information by States is also available for limited distribution.

Each wetland area or group of areas was also classified into one of 20 ecological types based mainly on location, salinity, vegetation, and water depth during the growing season. These 20 types are described in *Classification of Wetlands of the United States, Special Scientific Report—Wildlife No. 20*, June 1953, issued by the Fish and Wildlife Service.

A waterfowl-value rating was also assigned each delineated wetland area. Categories of high, moderate, low, and negligible values were established. These apply only to the State in which the wetlands are located and are judgment evaluations by waterfowl biologists on the basis of current conditions of the habitat and present usefulness to waterfowl. They do not reflect potential use that might be expected if the areas were developed specifically for waterfowl.

Use during the production, migration, and wintering periods were all considered in deciding the rating for each wetland unit. The data as presented here, as a general rule, do not show use for any one particular waterfowl activity. In Minnesota, for ex-

ample, more than a million acres of wetlands received a high rating—more than in any other State in the country—but most of them were so rated because they furnished good places for ducks to stop during the hunting season and are important from that standpoint. The remainder of the high-value wetlands in Minnesota is nesting habitat. Considering production use alone, however, the high-value acres in Minnesota produce far fewer ducks than North Dakota's half-million acres of top-quality habitat.

Accompanying this chapter are one table and two maps. The table shows by States the total number of acres delineated in the inventory according

The Value in 1955 of Wetlands to Waterfowl Based on State-Unit Determinations (Acres)

(Values not comparable between States)

State	*High*	*Moderate*	*Low*	*Negligible*	*Total*
Alabama	26,500	249,600	1,092,200	230,100	1,598,400
Arizona	16,500	11,400	500	....	28,400
Arkansas	926,600	699,400	1,496,700	662,700	3,785,400
California	317,800	176,200	57,600	7,700	559,300
Colorado	35,800	101,600	211,900	55,100	404,400
Connecticut	6,900	8,000	4,800	3,700	23,400
Delaware	24,600	40,700	49,600	16,400	131,300
Florida	423,000	1,659,900	6,585,200	8,517,200	17,185,300
Georgia	20,900	440,400	1,428,900	4,029,300	5,919,500
Idaho	59,300	23,100	21,400	5,100	108,900
Illinois	75,700	196,100	112,700	42,800	427,300
Indiana	151,600	68,900	33,600	29,300	283,400
Iowa	57,100	51,600	....	29,400	138,100
Kansas	120,800	65,900	17,500	....	204,200
Kentucky	84,400	27,400	34,200	127,100	273,100
Louisiana	706,800	1,706,200	1,092,500	6,141,800	9,647,300
Maine	108,500	52,200	140,300	80,300	381,300
Maryland	112,600	87,800	51,100	38,500	290,000
Massachusetts	46,600	55,700	80,200	49,200	231,700
Michigan	310,500	2,013,200	430,100	463,300	3,217,100
Minnesota	1,274,500	778,800	2,991,600	....	5,044,900
Mississippi	316,200	682,200	854,700	736,300	2,589,400
Missouri	105,700	93,100	74,000	104,100	376,900
Montana	29,100	113,300	45,000	....	187,400
Nebraska	197,800	171,000	281,000	....	649,800
Nevada	109,100	70,400	13,000	....	192,500
New Hampshire	5,700	4,800	1,700	1,300	13,500
New Jersey	127,500	109,100	32,400	900	269,900
New Mexico	24,500	12,900	11,100	....	48,500
New York	99,800	35,700	55,100	22,200	212,800
North Carolina	81,100	38,500	505,200	3,429,800	4,054,600
North Dakota	554,900	653,600	314,800	....	1,523,300
Ohio	38,500	12,300	19,300	27,800	97,900
Oklahoma	18,500	133,800	127,400	....	279,700
Oregon	246,000	76,800	131,900	17,900	472,600
Pennsylvania	8,600	15,100	15,800	13,400	52,900
Rhode Island	1,900	2,100	4,000	17,400	25,400
South Carolina	10,900	194,400	1,495,600	1,676,100	3,377,000
South Dakota	161,400	414,200	176,400	....	752,000
Tennessee	447,600	128,200	128,600	123,600	828,000
	86,400	1,597,800	923,500	633,[illegible]	
Utah	249,400	342,100	315,800	267,100	1,174,400
Vermont	6,700	9,500	13,000	8,900	38,100
Virginia	28,300	85,900	177,700	249,200	541,100
Washington	54,300	53,900	68,100	56,900	233,200
West Virginia	1,600	....	2,200	....	3,800
Wisconsin	389,500	48,200	2,352,900	....	2,790,600
Wyoming	11,900	3,500	14,900	....	30,300
Total	8,818,900	13,616,500	24,087,700	27,915,200	74,439,300

to the four waterfowl-value categories. The distribution of high-quality wetlands used by ducks and geese is indicated on the map of the United States.

The continental map shows the distribution of waterfowl in the breeding and wintering periods. The data are based on annual surveys of the breeding and wintering grounds, conducted cooperatively by the Fish and Wildlife Service, the Canadian Wildlife Service, Provinces, States, and private conservation agencies. The map shows densities of ducks, geese, and coots throughout North America, rather than just in the United States. This was done to orient the relative importance of wetlands in the United States to the overall aspects of waterfowl management.

Within the United States, the wetlands inventory shows about 74.4 million acres being used in varying degrees by waterfowl. Of these acres, about 9 million are classed as high-quality wetlands, 13.5 million as of moderate value, 24 million as of low value, and 28 million as of negligible value. These wetlands, depending on their location, supply breeding sites, wintering areas, and places to rest and feed during migration. All, except possibly the negligible-value wetlands, have important roles in the management of waterfowl, and some are capable of improvement. We shall now explore the more important aspects of waterfowl management as it relates to land use and wetland preservation.

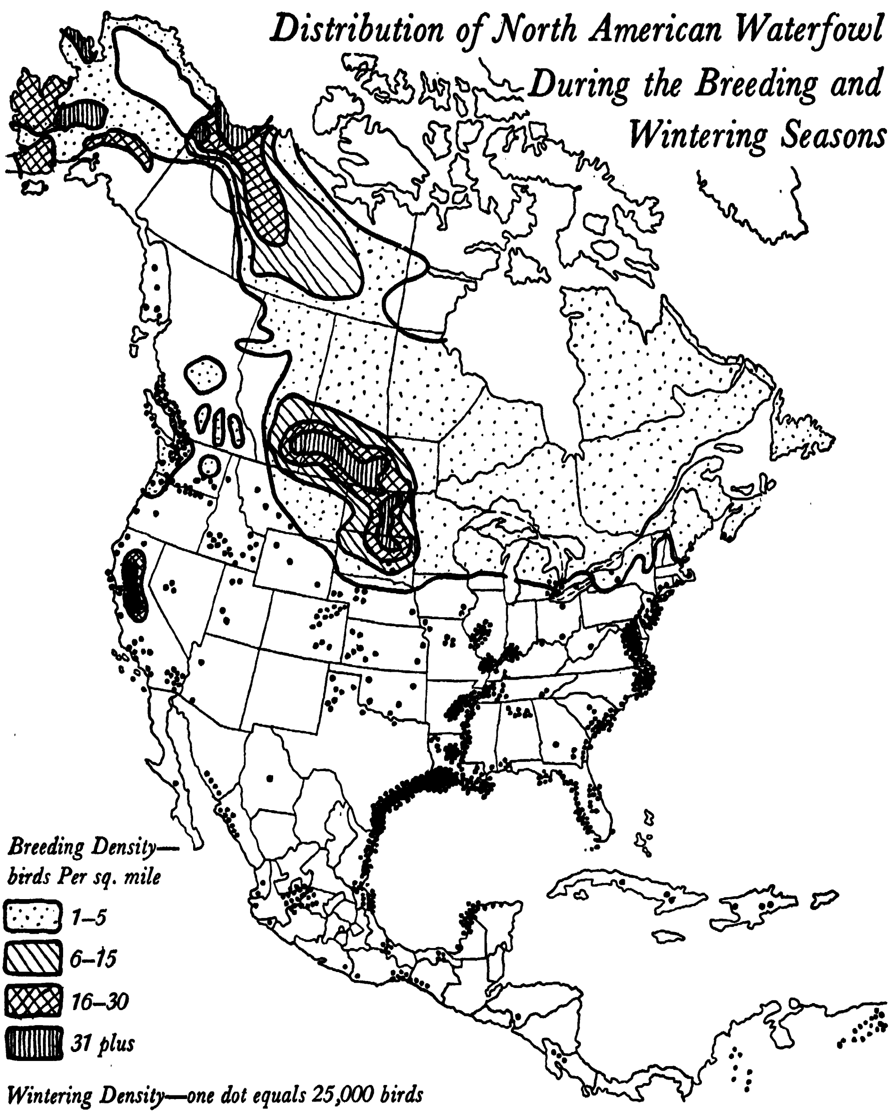
MANAGING WATERFOWL is a complicated job. Actually, though, it is little different from managing a domestic food animal, since the end result is to satisfy the consumer over a sustained period. Suppose the Federal Government were responsible for managing all the beef cattle raised on private land in the United States. The Government would have to know how many cattle to maintain, how much range would be needed to feed them, and how it could harvest enough animals in the right places at the right time and still leave enough to produce an adequate crop the following year. But, more important, the Government would have to do this in some manner agreeable to the landowners, or the program would certainly fail.

So it is with waterfowl. We must determine the optimum waterfowl population to maintain; the amount and quality of living space, or habitat, required to support this population; how the dedication of this land to waterfowl production, with or without other concurrent uses, can be effected in harmony with agricultural land-use programs; and how the hunters and landowners may participate in the total job of producing and managing waterfowl and also share in the harvest.

To many sportsmen, an optimum waterfowl population would be reached only if the skies were darkened by countless numbers of birds that could be harvested with little regard for seasons or bag limits. But maintaining that many birds is not compatible with present or future land-use practices in North America. The production of waterfowl and the production of food for human consumption are competitive in some respects. The demand for increased food production has already caused the drainage of a great many acres of wetlands. That means that the potential for producing sky-darkening numbers of waterfowl is gone forever.

In some parts of the country, particularly California, the amount of wetland has already declined to the extent that in years when breeding conditions result in above-average flights of waterfowl the birds turn to agricultural crops as a source of food. When the circumstances are such that the birds arrive before the crops are harvested, serious losses occur.

The depredation problem is acute also on the Canadian Prairies. There a large number of birds are being raised in a grain-growing region where, under certain circumstances, harvesting methods make the grain available to the birds. There is a definite need



for working out better depredation-control measures in the region. Therefore, the amount, quality, and distribution of wetland habitat that can be made available to waterfowl, plus the extent of agricultural crop depredations, can be used as a means of determining roughly the optimum level of waterfowl populations that should be set up as an objective.

Once an objective in terms of an optimum population level has been decided, waterfowl management is concerned with three major activities: Production during the breeding season; maintenance of an adequate breeding population from the end of one breeding season to the beginning of the next; and distribution of the harvest of surplus birds among the sportsmen of the continent. Each of these activities is limited by the availability of wetlands.

Waterfowl are exacting in their re-

quirements during the breeding season. There is a limit on the number of ducks and geese that will accept a given habitat unit for breeding purposes. The amount and quality of breeding habitat therefore determines the number of waterfowl that can be produced annually in North America.

Approximately one-fifth of the continental waterfowl crop each year is produced within the United States. Of the waterfowl in the United States during the spring and summer, almost three-fourths find breeding sites within the prairie regions of North Dakota, South Dakota, Minnesota, and Montana. Most of the rest are produced in States of the Northwest. Only about 6 percent come from States in the Northeast.

Almost half of the continental wetlands that produce waterfowl are in regions devoted primarily to agriculture. In the United States, almost all of the breeding habitat is so situated.

Although the expression "good weather for ducks" seems to imply that ducks thrive on rainy weather, the reverse is closer to the truth. During the breeding season particularly, ducks and geese require water, but excessive rainfall is detrimental to successful nesting and rearing of broods. The most productive nesting areas on the continent are where the annual rainfall is 20 inches or less. Areas that are dry periodically often appear to be more productive than are areas that remain flooded continually. North-central grassland prairies are characterized by hundreds of thousands of normally dry depressions which are filled by rainfall only about 2 to 4 years in 10. When this additional water occurs in the grasslands, duck production is considerably increased.

Another factor of importance is the size of the individual wetland areas. For example, in North Dakota the individual wetlands average somewhat better than 2 acres, while in southeastern Saskatchewan they average less than 1 acre. Production from each wetland unit is about the same in North Dakota and in Saskatchewan, so the difference in average size means that the average production per acre of wetland in Saskatchewan is more than twice the average in North Dakota. It is a fact that small potholes and marshes collectively produce more ducks than an equal acreage of large areas.

Between one breeding season and the next, wetlands are also essential to waterfowl, but in a different way. As the birds migrate south and set up winter territories, isolation is no longer sought by pairs. Rather, the birds become gregarious then and gather in flocks. Very large numbers of birds can now be accommodated on relatively small areas, provided there is sufficient food and a water area on which to rest.

It is not always necessary that food be obtained solely from wetlands. Some species of waterfowl show a preference for cereal grains even when natural aquatic foods are available. Agricultural lands in the vicinity of deeper water areas become acceptable waterfowl habitat for those species.

Waterfowl are highly mobile during the fall and winter season and have shown considerable ability to shift to more favorable locations. Even though waterfowl, for their actual survival during the fall and winter periods, may not need all of the wetland areas they now have, an abundant and well-distributed system of wetland areas is essential if the birds are to be harvested adequately and equitably.

Ducks and geese can migrate long distances between one stopping point and the next, but they are easily induced to make a more leisurely trip if good habitat for feeding and resting is available along the way. If the birds are not induced to stop by means of attractive wetlands, the opportunity for harvest along migration routes is limited. The same principle holds true for States in the breeding and the wintering areas—that is, a wide scattering of attractive wetland areas is a necessity if hunters in each State are to

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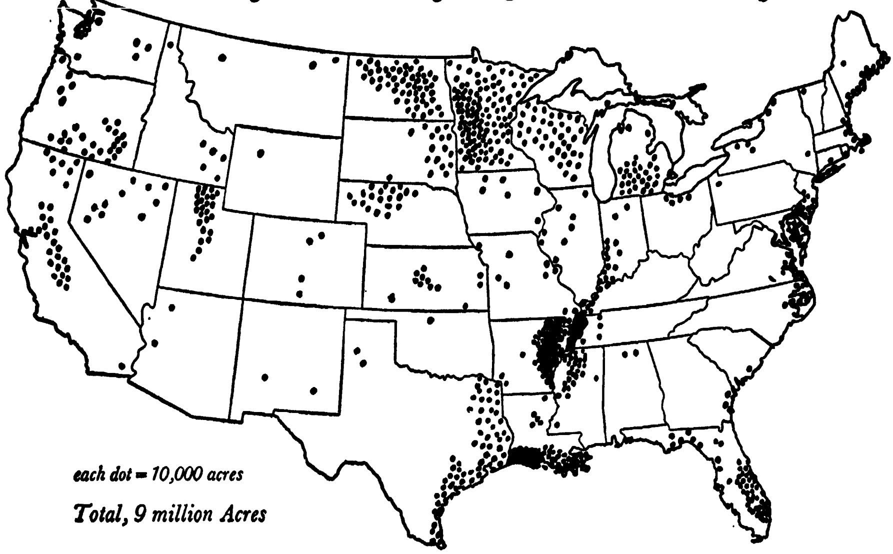
Distribution of Wetlands of High Value to Waterfowl



have some chance at good wildfowl shooting.

Much of the most attractive habitat where birds may be harvested has been purchased or leased by private individuals in recent years. The number of guns on these holdings generally has been limited as a means of improving the quality of shooting. As a result, a relatively few individuals are holding large numbers of waterfowl for extended periods during the shooting season and harvesting a small percentage of them. As this trend has developed, more and more waterfowl hunters have been forced to shoot on areas where the opportunity to kill a bird is limited. From the standpoint of equitable opportunities, therefore, there is need for purchase of additional wetlands to serve as public shooting grounds.

With public hunting opportunities there is need also for public ownership of places where waterfowl can seek refuge. Concentrated gunning will drive birds from an area. A sanctuary area with an attractive food supply will hold some species of waterfowl in a heavily gunned region, however. A well-integrated system of refuges and public shooting areas is necessary, therefore, for the proper distribution and harvest of the waterfowl resource.

After the hunting season, the need for the wetlands strictly as wintering grounds is at present most critical in the Pacific Flyway. In California, which regularly winters more than half of the Pacific Flyway population of waterfowl, a shortage of natural wetland habitat has forced the birds to turn to agricultural crops for food. Although the birds fare well on such crops as rice and lettuce, this serious depredation has necessitated special regulations that permit heavier harvests of the species—pintail and widgeon—doing the most damage. Obviously, reduction of population can be only an emergency and interim solution, because the procedure, if followed to the full requirement, could lead to a virtual elimination of important species of waterfowl.

Additional wintering habitat in such problem areas as California is critically needed, but it may not be the complete

answer to depredations. Ducks of several species have developed a preference for cereal grains over natural aquatic foods. Grainfields near water areas on which the birds can rest constitute satisfactory habitat during much of the fall, winter, and early spring for several species of ducks and for Canada geese. Rice growing in particular, with its flooded fields, offers particularly attractive conditions. To combat depredations, therefore, it has become necessary to make cereal grains available to waterfowl in addition to natural wetland foods. Today, many of the public waterfowl-management areas contain uplands where thousands of acres of cereal grains are grown.

FROM THE point of view of land use, administrators of wildlife constantly are faced with the problem of how much land should be placed in public waterfowl areas and what would be the best public policy dealing with drainage and flood-control projects that deprive waterfowl of top-quality habitat. Land-use agencies ask such questions as: How many acres of wetlands are needed to save ducks from further reduction in numbers? What is the plan for dedicating these lands for that purpose? Where are the valuable waterfowl wetlands located—those that should be spared from reclamation projects and dedicated to the use of waterfowl?

The inventory of wetlands helps answer the last of the questions. We have no simple answers to the others. Some are inclined to reply that since we have lost so much waterfowl habitat already, no further losses can be tolerated. Others believe that the essential wetlands can be selected, placed in public ownership, and managed for waterfowl, thus solving the problem of dwindling wetland acreages. Neither answer is adequate in itself.

Waterfowl administrators find themselves in the position of opposing drainage that would destroy waterfowl habitat, while at the same time they are forced to recognize that demands for wetlands to be reclaimed for dry-land use cannot always be denied.

Opinions of expert forecasters vary on how much land will have to be placed in agricultural production to support the future population of America and on how much of the growing demand can be met by increasing production on present croplands. A great deal will depend on how expertly cultivated acreages can be protected from the ravages of erosion and misuse and how fast improved cropping techniques can be applied.

THE DEPARTMENT OF AGRICULTURE states (*Major Uses of Land in the United States*, 1953) that there are some 50 million acres of wet and overflow lands in Continental United States which, if drained, would be suitable for productive agricultural uses. About 30 million of these acres are now partly in cultivation and 20 million acres are undeveloped lands subject to complete clearing and drainage programs. If the 1945–1952 trend in land development continues, we can expect that 15 million of the 20 million acres of undeveloped wetlands eventually will be used for cultivated crops, after flood protection, drainage, and clearing.

The loss of these 15 million acres of natural wetlands would indeed seriously affect waterfowl if the land were located where use by ducks is important. Experience has shown that the best waterfowl lands are often those having the best agricultural capability.

Data published by the American Society of Civil Engineers (*Drainage in the Humid Areas of the United States*, July 1954) show that 26,713,205 acres of land were benefited by open-ditch drainage, with financial assistance from the Agricultural Conservation Program between 1942 and 1952. We know, of course, that only a small percentage of this drainage affected marsh and open-water areas, but when such tremendous land areas are involved even a small percentage is significant in its effect on the diminishing waterfowl-habitat base.

This is particularly so when it is realized that 48 percent of this federally assisted drainage occurred in the North Central States, where the bulk of the duck-breeding wetlands in the United States is located.

The rate of drainage in the future will depend on economic conditions generally, the demand for crops that can be raised on such lands, and the State or Federal aid that is available to landowners for drainage. Alternative uses of wetlands without drainage have so far played a relatively insignificant role in determining the fate of such lands.

It is not enough to say that the only way to save waterfowl habitat is to stop drainage of wetlands. In addition, there must be general agreement that practical means are available to preserve the wetlands base. Just as in any other resource-conservation endeavor, the waterfowl conservation program must be a cooperative one, with individuals, local groups, and State and Federal agencies working together and sharing in the harvest. We need guidelines that agencies and individuals alike can follow in planning the future use of the remaining wetlands of the Nation.

Must we plan to reclaim every possible acre for agricultural and industrial expansion, or may we now make provision for safeguarding the two inseparable resources of waterfowl and wetlands?

There is no valid evidence that ducks must give way to civilization, but unless positive action is soon taken to provide for their future, they will be lost through default.

Wildlife administrators are also faced with the inescapable fact that it is not feasible to put into public ownership all of the wetlands necessary for producing and maintaining an adequate waterfowl population—particularly in the indispensable breeding grounds of the North Central States and the Prairie Provinces, where almost all of the breeding is on private lands.

Duck production is intimately and firmly linked with the millions of privately owned small water and marsh areas scattered throughout this farming region. There appears to be no practical way of placing in public ownership more than a small percentage of the acreage needed to maintain present production.

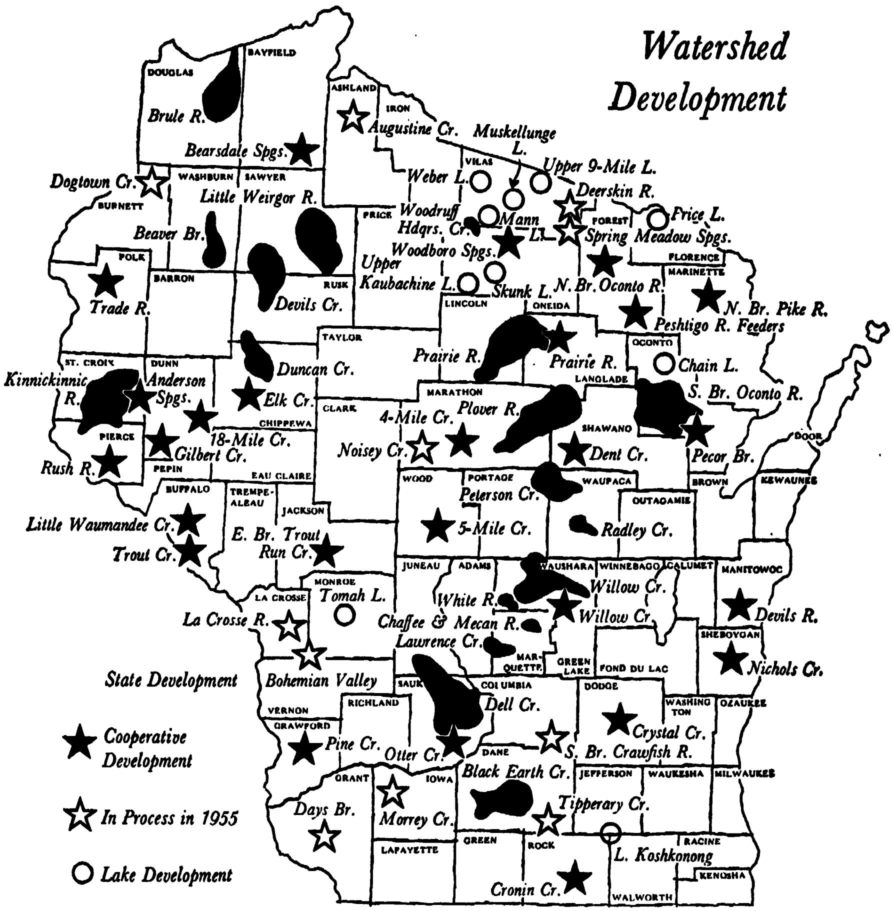
This is not to say that State and Federally owned areas are not needed in the breeding range of ducks. Such areas are essential to managing the waterfowl resource, but they are supplementary to (rather than a substitute for) the millions of acres of duck nesting habitat on private farms. Thus the farmer is a key man in the future of waterfowl.

Nearly 5 million acres of land have been acquired by the Fish and Wildlife Service and the State Conservation Departments for waterfowl management since 1935. These public areas are scattered throughout the breeding and wintering ranges and along the principal migration routes.

The longterm goal is at least 12 million acres in Federal and State ownership. But in view of the total acreage of wetlands now used by waterfowl (23 million acres of high- and moderate-value wetlands alone) it is not likely that even the most ambitious acquisition program could do the whole job.

The principal contribution of public ownership of waterfowl areas is their permanency for waterfowl use. These areas will forever be dedicated to and in many cases improved for migratory birds. Water-control structures on most waterfowl-management areas assure permanent habitat for ducks and geese, regardless of drought periods. During such periods, the use of these areas is greatly increased.

Preservation of wetlands for waterfowl is obviously a cooperative task which, aside from its international aspects, involves programs of State and Federal land-use agencies, State and Federal wildlife agencies, and private landowners.



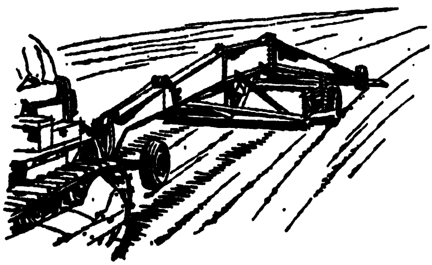
Activity location map showing Wisconsin Watershed Development Program (see page 582).

Often a landowner does not realize that a marsh he plans to drain has any real importance to the overall duck population or has any real value to him in its natural state. Or if he does realize it is important to ducks he may reason that it is not his business to protect a public resource on his private land if the land can return more profit to him if drained. We need practical methods to encourage landowners to keep their wetlands wet when high waterfowl values are involved.

That is where Federal and State land-use and water-control agencies fit into the picture. Theirs is the job of conserving all of the Nation's soil and water resources. It is reasonable to expect that in their land and water-use programs they should do their best to include plans for the protection and wise use of a valuable public resource like waterfowl. They are the ones who have the greatest influence on land-use changes, the ones who can help discourage drainage on private lands and even improve and create waterfowl habitat.

During the past decade or two an accepted method for encouraging needed conservation measures has been the use of incentive payments to land-

owners. Public funds have been used for this work, justified on the premise that good soil and water conservation is in the longterm public interest, even though the increased food and fiber resulting from such conservation are actually private resources. There is little opposition to such reasoning. There should be practically no opposition if public funds were used to benefit the public waterfowl resource.



The wetlands can be preserved, improved, and created on private lands if the land-use planners have the support of the people to do so, and if they have the authority to encourage wetlands management by giving technical and financial aid to such a program. As an example, instead of helping a farmer to drain a marsh in some important waterfowl region, he might well be given assistance to impound more water, plant waterfowl foods, and otherwise make the area more attractive to ducks. Potential benefits can accrue to him by managing wetland on his property—such as leasing his marsh for duck hunting, reaping a crop of wild hay, trapping muskrats, or using the impounded water for irrigation and recreation.

Each farm with a piece of wetland would have to be studied individually to determine how the area can best serve both the landowner and the ducks. State and Federal wildlife biologists as well as many agricultural technicians can help the farmer make those determinations. All that is lacking in most cases is a strong wildlife program based on land and water-use policies that recognize waterfowl and other wildlife as beneficial uses of agricultural lands.

The wetlands inventory can serve as a basic guide for selecting areas where waterfowl values should be given top consideration.

Now, the inventory should be put to work by making wetland-preservation programs an integral part of the work of public land and water agencies and acquiring more wetlands, whenever feasible, for State and Federal waterfowl management. Only by such a dual approach can the task of dedicating enough wetlands to accommodate a stable population of waterfowl become a reality.

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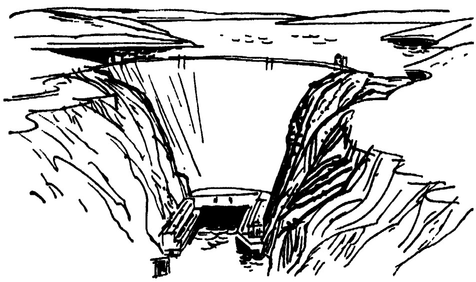
Burn down your cities and they will arise again as if by magic. But destroy our farms and the grass will grow on the streets of every city in the land.
—WILLIAM JENNINGS BRYAN

Hope rules a land forever green.
—WORDSWORTH

God will not seek thy race, nor will He ask my birth. Alone He will demand of thee, "What has thou done with the land that I gave thee?"—PERSIAN PROVERB

Pure Water for Farms and Cities



The Encroachment of Salt Water Into Fresh

Garald G. Parker

The gradual entrance of salt water into fresh-water aquifers is serious and widespread. It occurs in almost every State and Territory. It is costly in terms of money, time, energy, and productivity. It has caused the abandonment of municipal well fields and of industrial water supplies. It has ruined productive farmlands and killed orchards. It has deterred or prevented industrial development, and it has hindered civilian and military operations in many ways.

Often we could save ourselves toil and trouble if, in planning private, corporate, and governmental works, we made the same thorough study of water supply that we do of the other elements of construction—engineering design, cost accounting, market analyses, and other points that pertain to the proper functioning of projected works. But too often we neglect the water-resources factors, of which salt-water encroachment is one.

Thus, because of inadequate planning, irrigation projects may fail because the fields become waterlogged and snowy-white with accumulated alkali; industrial plants may close because the wells have gone dry or the process water has become too highly mineralized for further use; cities may abandon their long-used source of water and search for replacements as saline water displaces the fresh water once assumed to be limitless.

Salt-water encroachment means more than the intrusion of ocean water into fresh water. As used here in its broadest sense, salt-water encroachment includes salts of sodium, calcium, magnesium, potassium, and other rarer elements. In general, if the dissolved solids in the encroaching water exceed 1,000 parts per million (ppm), it is classed as a saline water and considered here.

THE ORIGINAL SOURCE of all salines is in the rocky material of the earth itself. When rain or snow falls on the land, the water contains relatively little dissolved mineral matter. But not for long. As it moves over or through the soil and rocks it begins at once to dissolve their more soluble constituents. The amounts and kinds dissolved depend largely on the nature of the earth materials with which the water comes into contact and upon the length of time of contact.

From uplands, the water that is not evaporated or transpired moves to the lowlands, and eventually to the sea or to a lake that has no outlet. Perhaps it may enter the slow and deep circulation of the ground-water system and remain for centuries in artesian reservoirs. Whatever its path, the water

becomes more and more highly mineralized with time.

Thus the oceans are salty because of the dissolved solids poured into them by the discharge of water from lands.

Starting out fresh, a river pours its partly mineralized water into the ocean, where the salts are concentrated by evaporation. Some inland lakes, such as Great Salt Lake, have become salty in much the same manner. At or beneath the earth's surface in many places are beds of rock salt, anhydrite, gypsum, borates, and other evaporites. Many of the deposits were formed in the distant past when conditions were favorable for large quantities of sea water to be evaporated, as at places where arms or parts of the sea had been partly or completely cut off from the main body by crustal movement or by the building of bars. The cutoff areas may receive fresh supplies of ocean water by an opening in the barriers or seepage through them or by occasional floodings over the barriers. It is possible that the separations may be so thorough that no additional ocean water is added and the trapped waters eventually are dissipated completely, leaving evaporite deposits where a landlocked sea once existed.

Inland salt lakes and marshes are local sources of salinity. They may originate in a variety of ways but usually are formed in areas having hot, dry climates. Crustal warping or sedimentary processes create closed depressions. Good examples are Great Salt Lake in Utah and Searles Lake in southeastern California. The inflowing fresh water is concentrated by evaporation or inflowing, slightly saline water is further concentrated, and the salt lake or marsh is formed—frequently both. Such conditions may be responsible for the formation of deposits of salt, brines, and bitterns, quite apart from those formed by or near the ocean.

Brines are found not uncommonly in the rocks of the earth's crust. They often are associated with petroleum and gas, but they often occur in places where no oil or gas fields are present.

Many brine deposits are doubtless connate—that is, water was entrapped in the sediments as they were being deposited in the sea. Most connate waters doubtless have been modified since original deposition. Many have been enriched by subsequent chemical reactions with adjacent or enclosing reservoir rocks and thus have become much saltier. Others have been somewhat diluted by fresher water circulating in the deep ground-water reservoirs.

Similar to connate water, but of later origin, is the residual water often found in ground-water reservoirs of modern coastal areas. Most of these saline waters gained entrance into the aquifers when the land was flooded by high-level, ice-age seas. Most residual waters now are greatly modified from their original condition; usually they have been diluted and have undergone base, or cation, exchange. This is a naturally occurring process by means of which calcium (or magnesium) in the water may be exchanged for sodium (or potassium) in the enclosing rocks, or vice versa, depending on local conditions.

Another source of saline water is deep beneath the earth's crust, where water is a normal chemical constituent of the rock solutions known as magma. This type of water occurs beyond the downward limit of free liquid water in rock interstices. In places where magma rises into the upper parts of the earth's crust, it ultimately solidifies into rocks such as granite, and, in the process, water that was formerly dissolved or in chemical combination with other minerals is driven off. Such newly formed water is known as juvenile water.

Juvenile water may escape into the overlying and surrounding preexisting rocks by seepage or may be emitted through volcanoes, hot springs, or geysers. But not all, or even most, of the water from hot springs or geysers is juvenile water. Much of it is of meteoric (rain) origin; it sinks to depths where it comes into contact with

heated igneous rocks, then rises to the surface, often in spectacular fashion, as in Yellowstone National Park.

Some of man's activities increase the salt content of natural waters and thus create new sources of salinity—notably some irrigation practices and industrial processes.

IRRIGATION WATER normally contains some salts. When irrigation water is evaporated from the land surface or is transpired by plants, the salts are left behind. If provision is not made for removing the salts, they will accumulate until the land becomes useless for farming. If drainage is satisfactory and flow is sufficient to leach out and carry away the salts accumulated from irrigation in one field, the degraded water moves down in the aquifers or surface streams to the farm of another irrigator. As the water moves from the upper to the lower end of an irrigated valley or river basin, it may have become so highly mineralized as to be no longer useful when it reaches the lower end.

Some industrial, mining, and petroleum operations also create new sources of salinity. Examples are the salty waste liquors (bitterns) left after the refinement of table salt; the production of magnesium from brines; the salty waters that come to the surface with petroleum in many oilfields, and the mineralized waste waters from some mines.

WATER BECOMES heavier and denser as its salinity increases. Distilled water, which contains no dissolved solids, is a standard for measuring specific gravity and is assigned a value of 1.000. Normal ocean water containing approximately 35,000 parts per million of dissolved solids (including about 19,350 parts per million of chloride) has a specific gravity of about 1.025. Thus, fresh water is about 40/41 as heavy as ocean water.

S. K. Love, chemist, United States Geological Survey, made the following analyses of water from the Atlantic Ocean off Miami Beach, Fla., in May 1941: Calcium, 423 ppm; magnesium, 1,324 ppm; sodium, 10,970 ppm; potassium, 429 ppm; bicarbonate, 147 ppm; sulfate, 2,750 ppm; chloride, 19,770 ppm; bromide, 49 ppm.

Because sea water is heavier and denser than fresh water, the two liquids tend to remain separate. The fresh water occupies a position above and upon the salt water, but if there is turbulence where the ocean and fresh water come into contact, they soon become mixed.

In the tidal reaches of streams where salt water from the ocean has free access to the stream channels and where the flow of the fresh water is not great enough to sweep the sea water out, salt water commonly occupies the lower parts of the channels and extends inland as a blunt-nosed wedge that moves to and fro with the tides.

EVEN WHERE a stream enters the ocean or a bay, the fresh water keeps its identity for greater or lesser distances, depending on such factors as roughness of the bottom and strength and direction of winds. That aspect is only one of a general class of such phenomena known as density currents. Cold fresh water flowing into a warmer body of fresh water, or muddy fresh water flowing into a body of clear fresh water, behave in the same way.

As the fresh water flows seaward above a wedge of salty water in a tidal channel, the fresh water glides over and on top of the salty water with little intermixing at the interface, especially in the upstream contact zone. Nearer the ocean the zone of mixture becomes thicker and, depending on the amount of fresh-water flow, disappears at some place downstream or in the ocean.

With changing stages of river and ocean and with resultant head differences between fresh and salt water, a complex flow regimen may occur. Fresh water may cease flowing seaward entirely, while salt water moves inland. Both salt and fresh water may flow inland at the same time or flow

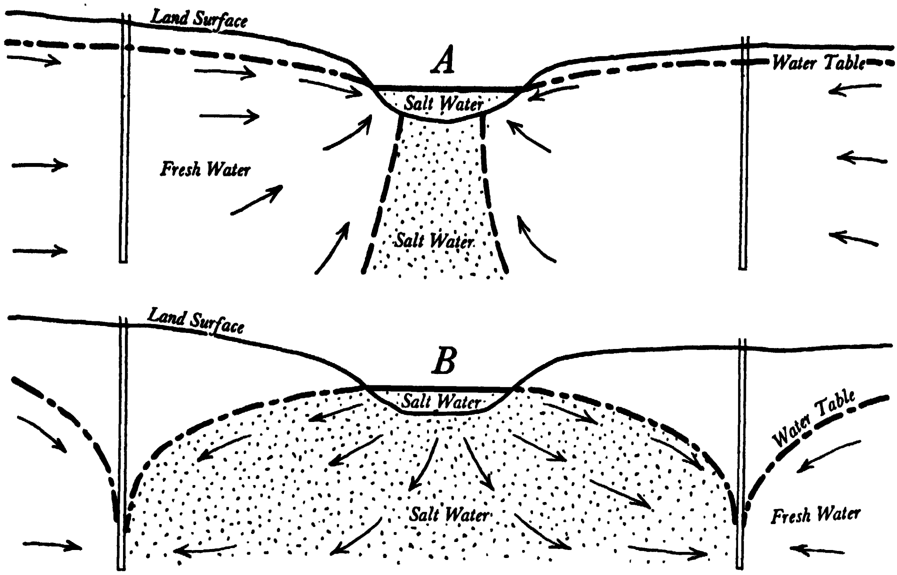


FIGURE 1. *This diagram shows the ground-water conditions near a tidal stream that usually carries salty water in its channel. The arrows indicate the direction of ground-water flow. Salt water underlies the stream channel as a trapezoidal prism. A is the movement under natural conditions before pumping takes place. B is the movement during pumping of ground water. A cone of depression surrounds each pumped well, the water table is depressed, and salty water encroaches into the aquifer.*

seaward at the same time, though not necessarily at the same rate; or sea water may flow inland, while fresh water flows seaward. The last is most common during periods of encroachment.

WHERE TIDAL STREAMS usually carry saline water in their channels, there is an elongate prism of salty water under and along the tidal courses if the underlying rocks are permeable and are hydraulically connected with the stream—again because of the differences in density and weight between salt water and fresh water. The salt water simply sinks down to the bottom of the permeable underlying rocks and fills the aquifer from top to bottom; fresh ground water flows toward the salt water and up over it as it discharges into the stream.

This condition is illustrated in the sketch, figure 1a, taken from the 1952 report by R. R. Bennett and R. R. Meyer on the Baltimore area, Maryland. When pumping of ground water is begun in such an area and continues until the water table is drawn down below the level of the water in the adjacent stream, salt water migrates toward the wells and the salt-water wedge widens proportionately. Eventually the salt water reaches the wells (as shown in figure 1, *B*) and the damage is done. Restoring the fresh water to its original position and balance with the salt water in such an area is a long and difficult or impossible task, and it may be very costly.

A STUDY of what happens when salt water advances upstream beyond the normal terminus of its wedge in a tidal canal was made by the writer and others of the Geological Survey in the Miami area, Florida, beginning in 1940.

The permeable limestone-and-sand ground-water reservoir of the Miami

area is known as the Biscayne aquifer. It is about 100 feet thick, and is underlain by relatively impermeable marls, which form the uppermost part of the confining bed known as the Floridan aquiclude. Highly permeable, the aquifer ranks with clean, well-washed gravel in its capacity to transmit water. The Miami Canal cuts the upper part of the aquifer and normally drains off large quantities of ground water to the sea while the salt-water tongue remains in the lower reaches of the canal, held in check 2 or 3 miles inland from Biscayne Bay by normal canal discharge.

However, in 1939, after somewhat more than a year of subnormal rainfall, the canal discharge dropped below a critical velocity, and the salt-water tongue began moving inland up the canal channel. Salty water eventually reached more than 10 miles from the bay and leaked down into the fresh-water aquifer throughout the length of the channel occupied by the salt-water tongue. When this occurred in that stretch of the canal opposite the Miami public-supply well field, the encroaching salty water soon appeared in the supply wells nearest the canal. Shortly thereafter, heavy rains fell, recharged the aquifer, and restored normal flow in the canal. The salt-water tongue in the canal was swept back to its normal position, and once again only fresh water occupied the canal adjacent to the well field.

But the charge of salt water that had leaked into the aquifer was not so easily disposed of. Cut off from its source and surrounded by fresh water on all sides, it created a mound of salty water resting on the floor of the aquifer. The mound gradually spread laterally and flattened out, much as a ball of tar might do on a hot sidewalk.

Caught in the prevailing movement of ground water toward the center of the well field, the mound of salty water slowly advanced. As it did so, it was constantly diluted by fresh water, and also was gradually pumped out as part of the municipal supply. Eventually

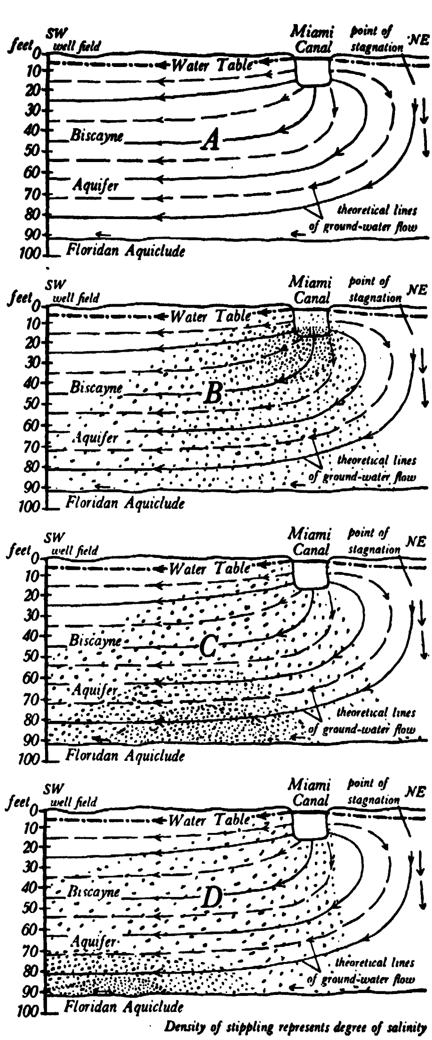


Figure 2. *A diagrammatic cross section illustrating salt-water encroachment by canal water in Miami, Fla. A, Canal contains only fresh water and because of pumping nearby stands higher than adjacent water table. Water moves from canal into aquifer toward well field, to left side of illustration. B, Salt water moves into canal and leaks out of sides and bottom of channel, the greatest concentration of salty water at first being immediately under the canal. C, Fresh water has replaced salty water in canal and salt water in Biscayne aquifer is now cut off from its source. It sinks to base of aquifer and creates a salt-water mound having highest chloride at bottom of mound. Mound moves to southwest, in direction of the local ground-water gradient. D, Flattened out and greatly diluted mound of salty water has moved into well field where it will be removed with municipal water.*

the mound of salty water was thus entirely disposed of. Figures 2, *A*, *B*, *C*, and *D* illustrate this series of events.

The principles governing the relation of fresh water to salt water can be illustrated by the ideal example of a circular island of permeable sand surrounded by ocean water and supplied with enough rainfall to develop a body of ground water in the sand.

Under those circumstances, a lens-shaped body of fresh water floating on and in equilibrium with depressed sea water occurs, as shown in figure 3, *B*. Because fresh ground water is 40/41 as heavy as normal ocean water, a column of this fresh water 41 feet high will weigh the same as a column of salt water 40 feet high. This is shown in figure 3, *A* and *C*. Thus for every foot that fresh water in such a system stands above sea level, it extends 40 feet below sea level. This is in accordance with the familiar Ghyben-Herzberg principle for estimating the depth to salt water in a freely pervious aquifer, the upper part of which contains fresh water. The principle, based on a static U-tube situation, states that the depth to fresh water is equal to a distance of (S–1) times the height of the water table above sea level, where S is the specific gravity of the saline water.

In examining the relations of fresh and salt water in the Biscayne aquifer of the Miami area, Florida, Russell H. Brown and the writer, both of the Geological Survey, found that observed field data matched quite closely those of European investigators, notably W. Badon Ghyben, Baurat Herzberg, and J. M. K. Pennick. Especially are Pennick's findings, for the polders of Holland, similar to those of Brown and me. The zone of diffusion between fresh and salt water in both areas is about 60 feet thick, and the 1,000-ppm isochlor lies at the middle of the zone.

In the Miami area, the contact zone between salt water and fresh water at the inland end of the encroaching salt-water wedge was found to be somewhat lower than it should have been in accordance with the Ghyben-Herzberg principle. It is believed that this divergence is due to joint action of two forces not included in the Ghyben-Herzberg calculation: The depressive effect that fresh-water flow has on the wedge, as suggested by M. King Hubbert in his theory of ground water motion, and the dissipation of the leading edge of the encroaching wedge of salt water through its mixing with (and being swept away by) the seaward-flowing fresh water; aiding in the mixing are the forces of molecular diffusion and the mechanical action of tidal thrust and pull in the shore-zone part of the aquifer.

Away from the seashore or large inland salt lakes, fresh ground water may come in contact with salt water in permeable aquifers. For example, if static conditions of no recharge exist, the fresh water will float as a flat sheet upon the saline water, as shown by lines *C–C′* and *D–D′* in figure 4. (This situation is theoretical, because if there were no recharge the fresh and salt water ultimately would become mixed by diffusion.) If, however, enough rainfall occurs to give uniform recharge to the fresh-water body, a Ghyben-Herzberg lens will develop, the water table will bow up, and the zone of contact between fresh water and salt water will bow down, as shown in lines *A–A′* and *B–B′* in figure 4. The work of John G. Ferris, of the Geological Survey, in Michigan, has indicated that the flushing out of connate waters by continuing recharge depresses the interface of fresh water and salt water to depths below stream level, as indicated in the highly schematic cross section (figure 4) and that the depths are nearly proportional to the altitude of the water table above the water level in the streams. The Ghyben-Herzberg principle calls for a 40-to-1 ratio if salt water having a specific gravity of 1.025 is involved. However, this proportionality does not apply strictly in areas adjacent to streams, where lines of ground-water flow are highly convergent.

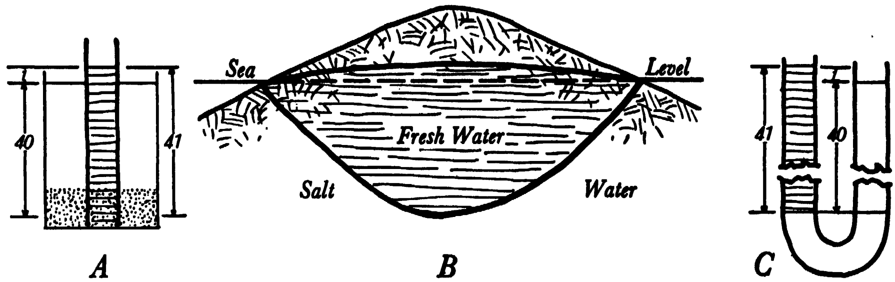


FIGURE 3. *Three diagrams showing the relation of salt water to fresh water, according to the Ghyben-Herzberg principle. A, Small, open-bottomed tube containing fresh water is placed in salt water and sand of larger container. Sand is indicated in diagram by stippling. Fresh water is free to move out but does not move beyond a point of balance with heavier salt water. Fresh water stands above salt water. C,* U*-tube contains fresh water in left-hand side and salt water in right-hand side. As in A, the fresh water stands higher than the salt water, 41 units high to 40 units high. B, Idealized cross section of permeable island in sea. Here rain water has seeped into the sand and produced a lens of fresh water that has depressed the heavier ocean water. The fresh-water lens floats in and on the salt water much as an iceberg floats on the ocean with most of its mass submerged. Periodic rains replenish the fresh-water lens.*

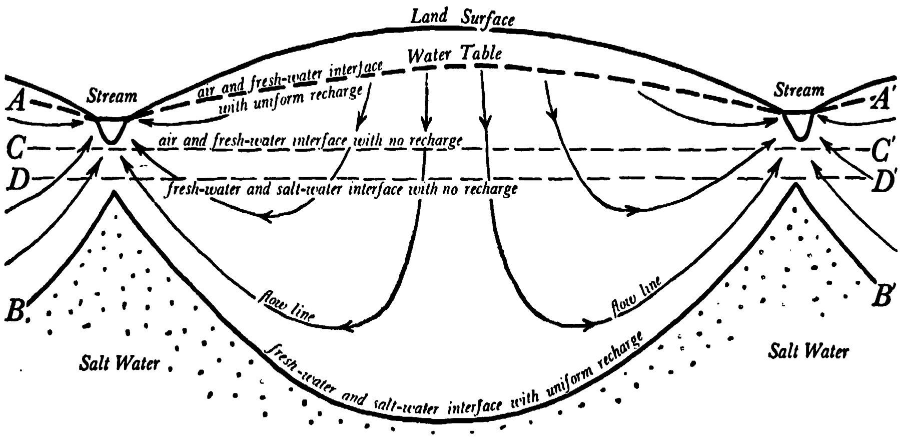


FIGURE 4. *Idealized cross section showing interface relations between fresh water and salt water in a uniformly permeable aquifer. Two streams cut the land surface; and in times of sufficient rainfall when the water table is high, they intersect the water table and drain away the ground water. This condition is shown by the water-table line A–A′. Given no recharge, the water table sinks below the reach of the streams, line C–C′. Salt water below the fresh water reacts for the condition of recharge as shown by line B–B′, and the fresh water above flows downward and outward, as indicated by the arrows. Salt water below the fresh water reacts for the condition of no recharge, as shown in line D–D′.*

In places where artesian aquifers in coastal areas dip beneath the sea and are hydraulically connected with it, the fresh water of the aquifers comes into balance with the salt water in a modified Ghyben-Herzberg relationship. The general relations between salt water and fresh water are expressed in figure 5, which is based on work of R. R. Bennett and R. R. Meyer in the Baltimore area, Maryland.

NATURALLY OCCURRING salt-water encroachment, the intrusion of saline water into fresh-water environments,

is as old as the geologic history of sedimentation. It occurs in nature in a variety of different ways. Time and again the seas have invaded the continents, only to retire eventually to the oceanic basins. Each time that the seas have advanced, a salt-water environment has replaced a fresh-water environment, and not only have marine sedimentary beds been deposited but saline deposits have been included.

A slow, worldwide rise of sea level is believed to be taking place. We in the United States have few accurate, long-time records of sea level. The earliest accurate records were begun in the port of New York in 1893. Others were made at San Francisco in 1898; Seattle, 1899; Baltimore, 1902; San Diego, 1905; Galveston, 1909; Key West, Fla., 1912; Pensacola, Fla., 1914; Ketchikan, Alaska, 1919; and Mayport, Fla., 1929. Our records, geologically speaking, are very short, and predictions based on them could therefore be quite misleading.

In general, during the period of record, the stations on the Atlantic coast showed very little change in sea level until 1930, at which time a definite rise began. The rate of rise in this region is about 0.02 foot a year, or 2 feet in 100 years. Thus, since 1930, there has been an increase in height of sea level along the Atlantic coast of about 6 inches. Gulf stations also generally indicate a rise of about 0.02 foot a year, but at Galveston, Tex., the rate of rise for the same period is 0.03 foot a year.

The Pacific coastal stations have shown a rise of about one-third as much as the Atlantic stations, except the Ketchikan station, which is showing a decline. That doubtless is due to crustal upwarping in that area, which is causing a rising coast line.

Changes in sea level of a relatively long-lasting nature may result from several causes, the most important of which are crustal warping, or faulting, which results either in enlargement or in diminution of the oceanic basins, and changes in the total quantity of water stored up as glacial ice on the land.

Existing records indicate that glaciers are generally melting at a rate faster than they are being renewed. That releases water to the oceans, adds to the total oceanic volume, and thus raises sea level. It is estimated that if all the glacial ice on land were to melt, the sea level would be raised more than 100 feet.

Sol M. Lang, of the Trenton, N. J., office of the Geological Survey, has computed that, if the rise of sea level continues at its present rate of 2 feet a century, the contact between salt water and fresh water in New Jersey coastal aquifers will recede inland at a rate of about 1 to 4 miles a century, depending upon the dip of the aquifer. That would create a serious situation in New Jersey and in other similarly affected coastal areas.

In flat and shelving coastal areas, a small rise in sea level may result in a wide inland migration of the sea, although only a small rise in the level of salt water. Where coastal areas have steeply dipping shores, lateral encroachment on the surface would be negligible, although lateral encroachment in gently dipping aquifers, if such are present, might be large.

Temporary, local rises in sea level may cause salt-water encroachment. Such temporary rises often accompany long-continued and strong offshore winds that pile up ocean waters on gently shelving coasts or in bays and inlets having relatively wide mouths facing the sea and V-shaped back shorelines. Large flats adjacent to the seashore also are likely to be invaded by salt water at such times.

Although the intruding salt water gets quickly into such areas, it is not removed from the soils and from the ground water so quickly. All but a few coastal States have some areas affected by natural salt-water encroachment of this kind.

In areas where crustal downwarping takes place, the effect is the same as if sea level were rising, and aquifers there

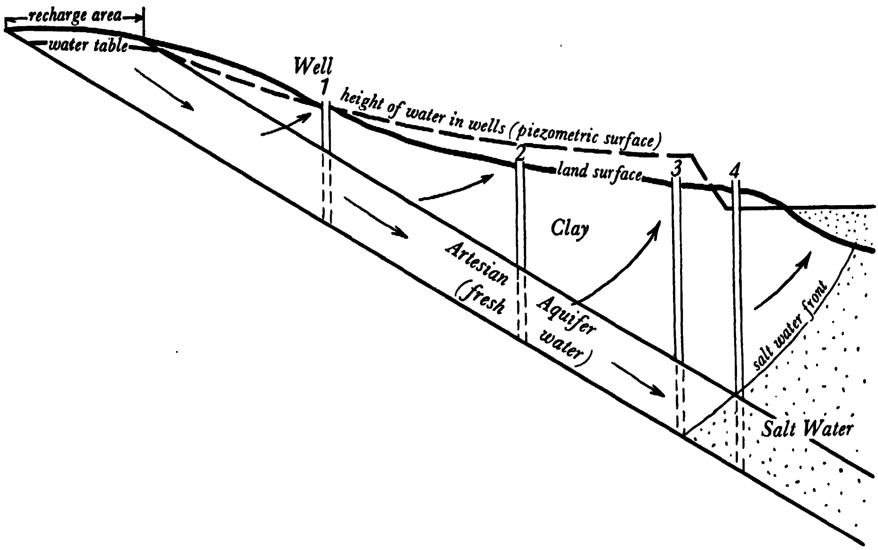


FIGURE 5. *Idealized cross-sectional diagram showing relationships between salt water and fresh water where coastal artesian aquifer crops out beneath the sea at some depth. This might be almost anywhere along the Atlantic coast from Long Island, N. Y., to Florida, along the Gulf Coast from Florida to Mexico, or along parts of the Pacific coast. Similar hydrologic conditions occur on some of the Hawaiian islands and elsewhere. The artesian aquifer crops out inland from the shore where it is recharged by rain. In this area the aquifer has a free air-water contact (water table). Downdip the aquifer is covered by relatively impermeable clay, and the confined (artesian) water rises in wells higher than the top of the aquifer. The level at which it stands in wells defines the piezometric surface. Note abrupt fall of the piezometric surface between wells 3 and 4, because well 4 ends in the zone of contact with salt water.*

are exposed to encroachment by salt water in direct proportion to the speed of their submergence under the sea.

Salt-water encroachment in nature may take place also where rock-salt domes thrust their way upward through overlying fresh-water aquifers. Salt-dome formations result from crustal warping that squeezes deeply buried salt beds enough to cause the salt to flow plastically. When it reaches a weak place in the overlying rock strata, the salt rams its way upward and thus relieves the pressure on the salt bed. Movement of fresh ground water past salt domes, such as those in Louisiana and Texas, may dissolve considerable quantities of salt and carry salty ground water down gradient from the salt domes. By and large, however, this is a major factor in only a few known cases of salt-water encroachment.

Crustal movements that result in rupture—faulting—of the earth's crust may result in naturally occurring salt-water encroachment. Such faulting may raise buried saline deposits to the land surface, where streams come into contact with the salts, or into the upper part of the crust, where they contaminate circulating ground water.

Many saline springs owe their origin to faults; in some places they are major sources of salt water. An example is Clifton Hot Springs, which empty into a tributary of the Gila River before that river enters the Safford Valley of Arizona. John D. Hem, of the Geological Survey, in his investigations of the springs in 1950, estimated that under varying conditions of discharge the Clifton Hot Springs produce about 9,000 to 25,000 tons of salt a year—almost 25 to 70 tons a day. The Clifton Hot Springs alone, by their discharge of 2 cubic feet a second thus add a small amount of water to the Gila but a burdensome load of salt.

Faulting on a grand scale has resulted in the development of the basin and range country of the West. Strata that once were flat have been broken into huge blocks of earth, tilted and crumpled, thrust up at one margin, and dropped down at the other. The result is a huge desert area of internal drainage, which has many valleys with no outflowing streams. The flat basins—sump areas—of the valley floors are called playas.

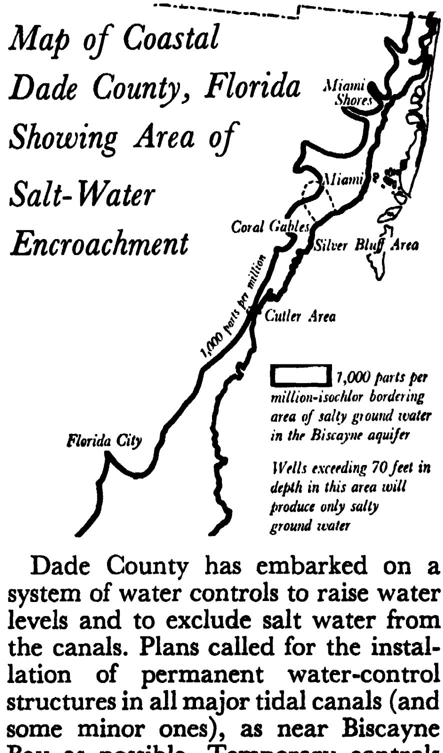
In the beginning the valleys were fresh-water domains. As time advanced and salts accumulated because of evaporation and subsequent concentration of salines in the playas, encroaching salt water became dominant. The process is continuing to this day. Death Valley is one of the best known of such fault-block valleys.

Even though these forms of natural salt-water encroachment occur, they take place very slowly, and at any given time in the earth's history salt water and fresh water in contact are in a fairly stable state of equilibrium. Under natural conditions, it may take centuries or even geologic ages for significant changes to occur—but when man's influences are felt, changes usually take place with great rapidity.

Drainage of the Everglades offers a good example of the results that follow man-made environmental changes. No one foresaw in 1910 that drainage of the mucklands would result in overdrainage of the coastal ridge on which Miami and the other cities of the east coast of Florida are situated. Nor, even if they had considered that the water table under Miami would inevitably be lowered as a consequence of drainage operations, would the drainage enthusiasts have envisioned the widespread and costly salt-water encroachment that has become a serious problem in that area.

The lowering of the water table by approximately 5 feet at Miami upset the naturally established equilibrium between salt and fresh water, and salt water began an inland migration that cost the city two major well fields (Spring Gardens and Coconut Grove) and its citizens along the coastal ridge the use of thousands of private wells.

Vegetable and fruit crops in the coastal areas of Dade County, which includes Miami, have suffered and at times were ruined by the application of unsuspectedly salty irrigation water, or by the rise of salty water to the root zones as the entire aquifer, top to bottom, in the coastal marsh areas succumbed to encroachment from the Atlantic Ocean and Biscayne Bay.



Dade County has embarked on a system of water controls to raise water levels and to exclude salt water from the canals. Plans called for the installation of permanent water-control structures in all major tidal canals (and some minor ones), as near Biscayne Bay as possible. Temporary controls placed in some arterial canals in 1944 and 1945 have effected significant results.

Dredging and deepening coastal waterways often bring encroachment by salt water. If such dredging operations allow salt water direct access to aquifers that previously contained only fresh water, or if the water table becomes so lowered that the Ghyben-

Herzberg balance is upset (as it was at Miami), salt-water encroachment is bound to follow. It is an aspect for consideration in the proposed plan to deepen the Delaware River by dredging between Philadelphia and Trenton. If facilities are constructed at the time of dredging to control streamflow and hold out salty water, the threat of salt-water encroachment would be greatly lessened. In the mid-1930's, construction of a sea-level canal across Florida was started but fear of lowered water levels and of salt-water encroachment caused abandonment of the plan.

THE COMMONEST type of salt-water encroachment is that induced by the use of wells. The encroachment may follow in any of several different ways.

In coastal areas, pumping of wells may cause a lowering of the water table. Once the cone of depression surrounding a pumped well or well field reaches a source of salt water, the saline water is pulled directly into the well or wells.

In some areas salt-water aquifers overlie fresh-water aquifers, underlie them, or are interstratified with them, the different aquifers being somewhat separated from one another by relatively impermeable layers of clay.

Wells that are improperly drilled, sealed, completed, or developed, or abandoned or leaky wells, may act as manmade channels of direct movement of the salt water into the fresh-water beds, and salt-water encroachment follows. It is a common type of encroachment and occurs in coastal areas and in many inland areas.

One other aspect of encroachment induced by wells should be considered. When wells tapping a Ghyben-Herzberg lens are pumped, salt water will rise toward the pumped well as the water table is lowered. But it will not respond so quickly as the water table does to pumping, for it is impeded by friction in the entire column of rocks extending down to the contact of salt water and fresh water.

C. K. Wentworth, in a report on the geology and ground-water resources of the Honolulu-Pearl Harbor area, Oahu, Hawaii, pointed out also that in freely permeable materials 40 times as much water (or more) rises from the bottom part of the lens as falls from the upper part of the lens. Thus we should expect greatly delayed response to pumping of fresh water from the upper part of a large Ghyben-Herzberg lens. In places where ground-water supplies have to be developed from such a system, precaution should be taken to avoid long-continued and deep drawdowns of the water table. In even small Ghyben-Herzberg lenses salt-water encroachment can be largely avoided or greatly delayed by judicious withdrawal of carefully developed shallow wells, infiltration galleries, or tunnels.

SALT-WATER ENCROACHMENT is a major problem in most oil-producing States. Often more brine is pumped out than oil. In the early days the brine was spilled on the ground or ditched away to sink into the soil. Nowadays the usual means of disposal are: So-called evaporation pits, which are ordinarily earthen reservoirs from which it is hoped that the water will evaporate rather than percolate; surface streams, which may or may not dilute the saline water sufficiently to do no harm; injection back into the substrata, sometimes into the oil sand at some distance from the well and sometimes into other permeable strata.

The evaporation pits have not worked satisfactorily. Often too many pits are required to store the prodigious quantities of salt water, and the pits overflow or detain the salty water for only a relatively short time before it seeps out through the earthen walls or down through the bottom. Perhaps fairly typical of this means of disposing of oilfield brines is that described by Alexander Nicholson, Jr., of the Geological Survey in New Mexico. He wrote that his area of study includes the largest concentration of producing

oil wells in the State. The earliest discovery was in 1926. Total production to January 1, 1954, is reported as 494,771,797 barrels of oil and 514,254,699 barrels (66,283 acre-feet) of brine.

He added: "Universally, brines are disposed of at or near the oil-well site by dumping into open dug pits, for the purpose of evaporating the water. A small amount of brine is used for circulation on drill rigs, and there is one brine-disposal well in the area. With those exceptions, all brine is pumped into disposal pits. The pits are simply gouged depressions with no lining. Most of the area is underlain by a thick layer of caliche, which is often impermeable, but in many of the brine pits the caliche layer has been broken up. Instances are reported where this has been done in order to promote seepage where the brine production exceeds the disposal capacity of the pit. None of the pits observed shows an appreciable accumulation of precipitates, let alone an accumulation commensurate with the brine produced.

"The average annual temperature of the area is about 60° F., and the humidity is usually low, both factors being favorable to a high rate of evaporation. Because of the method of construction of the pits, however, the virtual absence of precipitates, and the concentration of production within a relatively small area (200 square miles), a considerable amount of seepage to the area must be taking place."

The conclusion seems to be that encroachment of oilfield brines is taking place into the potable fresh-water aquifers of the area concerned.

Salt-water contamination of streams and resulting encroachment into public water supplies has been a major problem. In no oil-producing State are the surface streams free of oilfield brines. Once it was a common practice to release brines into streams, but now in most States it is either forbidden, or attempts are made to release brines only when streams are flowing at such rates that sufficient dilution is effected.

Texas has more than 500 widely scattered oilfields. At one time the State was without adequate laws to control disposal of oilfield brine. Not only were the water wells and fields belonging to individuals encroached upon by brines; the municipal supplies of such cities as Beaumont, Longview, and Graham also were damaged. Along the Pecos River, on small tributary creeks draining oilfield sites, chloride contents as high as 46,000 parts per million have been measured.

The injection of oilfield brines into deep aquifers already too salty for any other known use is the safest way to avoid salt-water encroachment from the oilfield wastes. It is more expensive than either evaporation-pit or stream disposal, but in the interest of conservation of our water resources it should be practiced more than it is. The water returned could be so injected as to serve as additional "water drive" in pushing oil into the pumped areas and to help maintain reservoir pressures. In some areas, where costs to individual operators would be too great, brine-disposal companies have been formed to build plants and operate injection wells for all operators who wish to make use of their services.

ARNOLD TOYNBEE, in his book, *Civilization on Trial*, states that, at the height of its flowering, the civilization of the Tigris-Euphrates Valley numbered about 40 million people who lived in comparative prosperity. Today fewer than 5 million live in the same area and eke out a precarious living. Dr. Toynbee credits the Mongols with slaying 30 million of those people and thus bringing about the downfall of their civilization.

A. Nelson Sayre, of the Geological Survey, however, credits two other reasons: Destruction by the Mongols of the canals and headgates of the irrigation system, and the accumulation of salt in the soil and ground water (a form of salt-water encroachment), which may have made the soil infertile even before the Mongol invasion.

Salt-water encroachment attendant on high-water-table conditions also may have been the prime factor, Dr. Sayre believes, in bringing about the downfall of the great Pima culture that existed in central Arizona about A. D. 1100–1300. The Pimas established a flourishing civilization based on irrigation and had constructed an elaborate system of canals that carried Gila River water to an irrigated area that may have comprised 250,000 acres. Through excessive use of irrigation water in an area lacking sufficient natural subdrainage, the water table rose and the soil became waterlogged; at the same time, the salt content of the ground water became excessive and salts accumulated in the soil—a prehistoric version of the early experience of the Salt River Valley irrigation project. Lacking ability to lower the water table, the Pimas were forced to abandon their lands.

MODERN HYDROLOGISTS attack the chemical aspects of such problems—and we are beset with them over much of our irrigated acreage today—by a study of the "salt balance." The term "salt-balance concept" means that the amount of soluble materials that must be removed from the soil and ground water of an irrigated area must be at least equal to the amount entering the area from all sources.

Of many examples that show the seriousness of the salt-balance problems in the United States, the Salt River Valley of Arizona can be cited. That area includes the valley lands near Phoenix and smaller tributary valleys nearby.

The Salt River Valley is a typical basin-range structure. Boundary faults define its sides, beyond which fault-block mountains have risen. The valley, or down-dropped area, has been filled partly by sand, gravel, silt, and clay—debris from the wastage of the mountains. The rock floor beneath the valley is not smooth. Cross-faults and an unevenly eroded surface of pre-valley rocks make for shallow- and deep-filled areas. Surface water flows in the river channel and from the channel bottoms down to the bedrock, ground water flows in the same general direction. River water and ground water are in hydraulic connection and exchange freely.

Both streamflow and ground-water flow bring water into the upper end of the valley and also remove the outflow from the lower end of the valley. Irrigators meanwhile have used the in-transit water over and over again.

With each use the water becomes saltier and saltier. John D. Hem, of the Geological Survey, estimated that in 1951 an excess of at least 350,000 tons of salines was deposited in the valley, in which, therefore, a serious salt-balance problem exists. Where the causes of local salt accumulation can be determined, it should be feasible to combat the salt encroachment and prolong indefinitely the use of the irrigated lands.

INDUSTRIAL WASTES have become important sources of salt-water encroachment in some parts of our country. Proper planning and the taking of adequate precautions would prevent needless loss of precious water supplies through the careless or indifferent handling of industrial wastes. However, it has always been easiest and cheapest at the moment to store saline wastes in surface pits or to dump them into a stream nearby; and lacking laws for controlling such industrial-waste disposal, many communities have been unable to protect themselves against it.

Nowadays there is a general awareness of the dangers in improper handling of industrial wastes. Many States and communities have enacted regulatory laws, and many industrial plants have voluntarily taken adequate means of controlling their saline wastes.

The Muskingum River Valley is an example of salt-water encroachment in an industrial area. The Muskingum River drains the eastern part of Ohio and empties into the Ohio River at Marietta. Two tributaries to the Mus-

kingum, the Tuscarawas River and Chippewa Creek, are major elements in the problem.

About it, Stanley E. Norris, of the Geological Survey, wrote in 1954: "Salt-water contamination of the Tuscarawas and Muskingum Rivers is caused by the discharge of calcium chloride and sodium chloride wastes into the Tuscarawas River above Clinton and from the discharge of sodium chloride wastes into Chippewa Creek at Rittman. The wastes originate from the manufacture of chemicals from saturated artificial brine, pumped from deposits of rock salt, which underlie approximately 9,000 square miles in eastern and northeastern Ohio. The deposits are associated with the Salina formation, the basal formation of the Cayuga group of late Silurian age (deposited about 325 million years ago). At Barberton the salt deposits are about 150 feet thick and lie at the approximate depth of 2,750 feet.

"The effects of chloride contamination extend at least to the mouth of the Muskingum River, a distance of more than 100 miles from the source of the waste products.

"Ground-water supplies pumped from glacial sands and gravels in the Tuscarawas and Muskingum Valleys have been affected by induced infiltration (caused by pumping) of streamflow into the aquifers. Wells in southeastern Barberton have been abandoned because of salt-water encroachment, and the ground water in the Tuscarawas valley in that area has been found to contain more than 20,000 parts per million of chloride. Farther south, at Coshocton, the city well field was abandoned and a new supply developed at a cost of more than 400 thousand dollars.

"The chloride problem at Zanesville is acute. The city has 24 wells drilled into glacial gravels along the Muskingum River. Periodic analyses in 1949 and 1950 show the water to have ranged between 80 and 222 parts per million.

"At Marietta, where the city supply is also from wells in the Muskingum valley, there has been a marked increase in chloride in the past 10 years."

The salt-water encroachment of the entire area stems from two major industrial operating plants, both of which have taken steps to eliminate contamination by saline wastes. One concern announced plans for disposing of its wastes through wells into abandoned parts of its former workings. The other engaged a consulting firm to formulate plans for correcting its waste-disposal practices. But even when the saline wastes are poured no longer into the Muskingum River valley, it may be decades before the salt-water contamination of the aquifers is removed and the aquifers restored to their original state.

THE FOREGOING has described the general nature of salt-water encroachment. For more specific details of the encroachment and salt-contamination problems in the United States, let us consider reports from scientists of the Geological Survey in 1954:

Arizona.—L. C. Halpenny, Tucson: Serious encroachment problems exist in several areas, notably in Maricopa and Pinal Counties. Sources are chiefly saline playa deposits formed in Pleistocene time and recirculated irrigation waters in the valleys of the Salt and Gila Rivers. The first is chiefly of local effect, but the second is extensive.

Arkansas.—P. Eldon Dennis, Little Rock: Salt water is present at depth in a few aquifers containing fresh water in their upper parts. Many wells developed in those aquifers have become salty; some have become so salty that the city well fields have been abandoned, as at Brinkley and Marianna.

California.—J. F. Poland, Sacramento: Many places are troubled with salt-water encroachment and related problems, especially some ground-water basins bordering the Pacific Ocean. Heavy pumping there has lowered the water table below sea level and salt-water encroachment has resulted. Areas of most serious encroach-

ment are along the west and south coastal basins of the Los Angeles coastal plain, and the Santa Clara Valley around the southern part of San Francisco Bay and at the mouth of the Salinas River valley. Encroachment of lesser magnitude has occurred beneath the Oxnard Plain in Ventura County and in several small valleys in San Diego County.

West of Long Beach and near Santa Monica, partially confined shallow aquifers of Recent age are open to the ocean; they are underlain by aquifers of Pleistocene age. Along the west coast, from the Palos Verdes Hills to Santa Monica, the Silverado water-bearing zone ranges in thickness from 100 to 500 feet and is open to the ocean for about 15 miles. There are no fault barriers within 3 miles of the ocean in the Silverado water-bearing zone and none at all in the Recent materials.

By 1951 salt water had invaded approximately 17 miles of coastline along the west and south coasts of the basin reaching as far as 1.5 to 2 miles inland by advancing through the open seaward ends of aquifers. The landward hydraulic gradient extended as much as 6 miles inland in 1950. Experimental remedial measures have been practiced at Manhattan Beach since 1952, by the injection of fresh water into a line of recharge wells about a mile in length, to raise the water table above sea level and thus create a "fresh-water dam." Plans were made to use treated sewage waste to recharge the aquifer and maintain the fresh-water dam. In addition, water rights are being adjudicated and quantity of pumpage is to be reduced.

Colorado.—Thad G. McLaughlin, Denver: Industrial saline wastes escaping from leaky evaporation ponds near Derby and Adams City northeast of Denver are suspected of causing salt-water encroachment into the aquifer that resulted in killing of crops by pumped irrigation water.

Connecticut.—Robert V. Cushman, Middletown: Salt-water encroachment has occurred chiefly at New Haven and Bridgeport as a result of pumping from wells. The salt water either moves in laterally from surface-water sources (indirectly from Long Island Sound) or rises from depth in the aquifers. Sometimes both sources may contribute to encroachment. A few industrial plants have had to abandon their wells and some others have alleviated their problem by reduction of pumpage, by economies in use, such as recirculation of water, or by spacing wells at greater distances to avoid excessive lowering of the water table.

Delaware.—William C. Rasmussen, Newark: Salt-water encroachment has occurred at four localities, threatens at another, and is the object of concern at two others. The most serious encroachment to date occurred at Lewes in 1943. Excessive demands for water were caused by rapid expansion of the military establishment there, and the water table was greatly drawn down. Simultaneously the Lewes-Rehoboth canal, carrying saline water, was dredged nearby. Salt water from the canal promptly invaded the Lewes well field, and it was abandoned. A new well field safely distant from the canal was developed. The old field may have been flushed of its salty water and it might therefore find limited use again. Concern has existed over the possibility of salt-water encroachment resulting from the proposed widening, deepening, and straightening of the Chesapeake and Delaware Canal.

Southern Florida.—Nevin D. Hoy, Miami: Salt-water encroachment problems are serious in several places. Aquifers presently or potentially involved are: Biscayne aquifer in Dade and Broward Counties; shallow (less than 100 feet) aquifers in the Lake Okeechobee-Everglades area and adjacent parts of Hendry County; shallow (less than 300 feet) aquifers in coastal parts of Martin, St. Lucie, and Indian River Counties; and the Floridan aquifer (principal artesian aquifer of the State). The latter is somewhat mineralized throughout the southern part of

Florida, the salinity being greater to the south, and at depth, in the aquifer. Some cities, as Fort Myers, Fort Pierce, and Fort Lauderdale, have suffered from salt-water encroachment. Fort Myers abandoned its well field in 1945 and developed a new well field safe from encroachment. Fort Pierce's well field has been sparingly used since salt-water encroachment showed in wells close to Indian River (a salty lagoon) soon after the well field was developed during the Second World War. Fort Lauderdale's well field has been threatened by lateral salt-water encroachment from New River and by vertical encroachment from residual saline water at depth in the aquifer. Several other smaller municipalities have suffered similarly or face potential encroachment.

Northern Florida.—Ralph C. Heath, Tallahassee: These areas have been affected by salt-water encroachment: Pensacola; Panama City; all of Pinellas County, except the central and northeastern parts; Ruskin; Tampa; and Daytona Beach. The encroachment occurs mostly in the Floridan aquifer and, with the exception of Pinellas County, appears to be solely due to local overdevelopment of the supply. In Pinellas County, besides overdevelopment of the supply, there may have been overdrainage through canals resulting in encroachment similar to that at Miami. St. Petersburg abandoned its old well field and developed a new one at a safe distance inland from Gulf of Mexico water.

Hawaii.—Dan A. Davis, Honolulu: Ground water occurs in gross accordance with the Ghyben-Herzberg principle. Thus a fresh-water lens floats on and in the surrounding sea water. During the 50 or 60 years since ground-water development on Oahu began, the part of the lens above sea level has been measurably reduced, its surface (water table) having fallen from about 40 feet above sea level to 25 or 30 feet. As a result of this change in height of fresh water above sea level, a rise in the salt-water and fresh-water contact has occurred, and the lens thus has shrunken. Salt-water encroachment has followed, but the encroachment in the Honolulu area is a slow process and, though pronounced, has not yet become serious. Encroachment has been observed elsewhere in the islands, as in the Lahaina area of West Maui and at Paia on the isthmus of Maui.

There is a trend toward the abandonment of drilled wells and the substitution therefor of "skimming tunnels." The tunnels are excavated below the water table so as to skim off the upper fresh water over a fairly large area, as contrasted to the rather limited area a well would draw from, and thus avoid overly deep drawdowns, with consequent uprising of saline water from below. Artificial recharge is being tried on both Oahu and Maui. Attempts are being made to divert excess surface water (flood runoff) into leaky reservoirs in the hope that the water will move downward into the aquifers.

Indiana.—Claude M. Roberts, Indianapolis: Salt-water encroachment in Indiana has occurred in several localities in or near oilfields. Oil-well brines have been disposed of through leaky evaporation pits or ditched into surface streams, and encroachment has spread into fresh-water aquifers. Some leaky and some unplugged but abandoned wells act as local sources of contamination. Encroachment, chiefly local, has been noted in Miami, Vigo, Clay, Sullivan, Knox, Daviess, Pike, Gibson, and Posey Counties. State and local efforts to reduce salt-water encroachment are under way. They include correctional procedures, such as abandonment of evaporation pits in favor of injection back into the oil-bearing formations; artificial ground-water recharge; and abandonment and sealing of spent oil wells.

Iowa.—Eugene H. Walker, Iowa City: Salt-water encroachment is not a major water problem in Iowa. One of the principal aquifers comprises the St. Peter sandstone, the Prairie du Chien formation, and the Jordan

sandstone. It contains usable fresh water and is widely tapped by municipal, industrial, and private wells. In several instances, poorly constructed wells, as at Altoona, North English, and McGregor, have extended into saline waters below the fresh-water aquifer and acted as conduits for carrying the salty water into the fresh-water aquifers. The remedy was found in properly sealing faulty joints in the well casings, once the leaky joints had been discovered by well-exploration methods.

Kansas.—V. C. Fishel, Lawrence: Salty water occurs at depth everywhere in Kansas. Salt-water intrusion into streams and encroachment into fresh-water aquifers is serious in many places. The principal saline sources are salt springs and salt marshes, industrial wastes and oilfield brines.

Salt marshes along Rattlesnake Creek appear to be the source of salt that changes the Arkansas River from fresh to saline below Sterling and Hutchinson. Industrial wastes are especially serious at cities where salt is mined and refined, as at Hutchinson and Lyons. Some encroachment from oilfield brines has occurred in nearly every major oilfield of the State. Largely through efforts of the Kansas State Board of Health, however, considerable progress has been made in reducing salt-water encroachment from oilfield brines through the development of better control and disposal methods. As in most other oil-producing States, so-called "evaporation pits" have been the chief sources of contamination. Most brines now are being returned to deep subsurface formations through disposal wells.

Kentucky.—M. I. Rorabaugh, Louisville: Saline water occurs at depth everywhere in Kentucky except in the Jackson Purchase. Salt-water encroachment into shallow fresh-water aquifers probably occurs in places through abandoned oil and gas test holes, especially in the eastern and western coal fields. There has been suggestive, though not positive, evidence of salt-water encroachment near Paintsville and Prestonville.

Louisiana.—A. N. Turcan, Jr., Baton Rouge: Salt-water encroachment has become serious in several places. One of the most important of these is near Milton, where saline water has encroached into the principal fresh-water aquifer (called the Chicot reservoir) from the Vermilion River and thus endangers the water supply of a large part of southwestern Louisiana. Other places where notable encroachment has occurred are Baton Rouge, New Orleans, Norco, and in and near several of the larger salt domes, as at Port Barre and at Chase.

Maryland.—E. G. Otton, Baltimore: Three principal areas of salt-water encroachment exist in Maryland—the Baltimore industrial area; the Army Chemical Center, Harford County, and the Crisfield-Westover area, Somerset County.

In the Baltimore industrial area, saline waters have encroached upon the three principal aquifers through leaky well casings and abandoned wells, and along the outcrops of the aquifers beneath Chesapeake Bay. An area of 6 to 8 square miles is involved. At least two means of controlling the encroachment are feasible—repair and sealing of leaky or abandoned wells, and "protective pumping" of the encroaching saline waste into Chesapeake Bay, thus diverting or removing it from the aquifers.

Michigan.—John G. Ferris, Lansing: Unplugged test holes and salt-water wells have aggravated Michigan's salt-water-encroachment problems by providing localized avenues of essentially infinite vertical permeability for the escape of deep mineralized waters. Such waters underlie much of the Michigan basin and occur as brines in the deeper parts of the basin everywhere. The brines are the sources of supply that have made Michigan one of the leading salt-producing States for many years.

Upward migration of saline waters has been induced by intensive local

development in a number of places, notably Grand Rapids, Pontiac, Royal Oak, Flint, Kalamazoo, Lansing, and Holland. In some instances the encroaching saline waters have been high in chloride or sulfate. Some minor encroachment has occured near salt springs.

Minnesota.—Robert Schneider, St. Paul: The problem is of little significance except in Kittson, Marshall, and Polk Counties, where deep-lying connate waters have encroached to an unknown extent upon overlying fresh-water aquifers, chiefly through unplugged or leaky wells that extend into salt water. The remedy would lie in plugging or repairing the wells.

Mississippi.—Joe W. Lang, Jackson: Salt-water encroachment in Mississippi stems mainly from oilfield brines and the Gulf of Mexico. Oilfield-brine problems here do not arise from pits and wastage into surface streams, for almost everywhere the brines are injected into the subsurface. The problems come from injection into deep, fresh-water aquifers. The oilfields principally concerned are Adams County, Helderberg, Tinsley, Brookhaven, Mallalieu, Banterville, and Soso.

Along the gulf coast, sea water gains access to the fresh-water aquifers in areas of heavy pumping, as at Pascagoula and Biloxi, and where tidal streams, in time of drought, carry salt water as much as 18 or 20 miles inland. The Pascagoula River is an example. Danger of encroachment exists in coastal artesian aquifers where artesian wells commonly flow to waste, thus lowering the pressure and disturbing the long-existing equilibrium between fresh water and salt water which in the past has been sufficient to hold salt water in check and prevent its inland migration.

Nebraska.—Charles F. Keech, Lincoln: Except in and around Lincoln, salt-water encroachment is not a major problem in Nebraska. At Lincoln many supply wells, including those of the former municipal system, tapped the Dakota sandstone, which in its lower parts carries saline water. In recent years salty water has encroached to such an extent that many wells have been abandoned. The city of Lincoln has developed a new supply from a shallow aquifer near Ashland, in the Platte River valley.

New Hampshire.—Edward J. Bradley, Durham: Salt-water encroachment of a minor nature has occurred along the ocean shore and up the reaches of tidal streams, such as the Piscataqua River. Many wells now salty have been in use for years, but recent equipping of such wells with electrically powered pumps has caused much greater draft than in former times and many new wells have been put into service. The greater withdrawals that result have upset the Ghyben-Herzberg equilibrium. Accordingly, salt water migrates inland.

New Jersey.—Sol M. Lang, Trenton: Salt-water encroachment is a potent factor in the water supply of New Jersey. At Newark salt water has been drawn into the aquifer from the Passaic River and Newark Bay by heavy pumping, but the dredging of the ship channels in the Passaic River, which contains salty water, doubtless had a heavy contributory effect by cutting through and removing relatively impermeable sediments from the river bottom and thus establishing good hydraulic connection between the river and the underlying aquifer.

Many other places in New Jersey are troubled with salt-water encroachment, notably the Raritan Bay area centering around South Amboy, the Atlantic City-Cape May area, and industrial sites along the Delaware River in western Salem and Gloucester Counties. Problems of salt-water encroachment are likely to develop almost anywhere along New Jersey's shore boundaries from Trenton to Cape May and north to Newark.

New Mexico.—Clyde S. Conover, Albuquerque: Three areas of concern are the area east of Roswell, southern Lea County, and the Malaga Bend area on the Pecos River.

The area east of Roswell is underlain by evaporite beds of limestone, gypsum, anhydrite, and halite (rock salt), which contaminate ground water flowing in contact with them. Heavy irrigation pumping has changed ground-water gradients in the area and induced a flow of this mineralized water into the irrigated area, the water of greatest mineralization occurring at greatest depths in the aquifer. On the basis of an incomplete investigation now underway, it is believed that there is a maximum feasible depth in which water still may be obtained over a large part of the area. Care in drilling wells to depths short of the highly saline water, the plugging of all wells containing highly saline water, and reduction of pumpage in the area would doubtless do much to increase the life expectancy of irrigation in this region.

Southern Lea County is an area in which encroachment stems from disposal of oilfield brines. The Malaga Bend problem stems from spring discharge of highly saline water into the Pecos River, which greatly increases its salt content and lessens its value to all downstream users. A study by William E. Hale and others of the Geological Survey points to the possibility of removing the brine by pumping it from wells into a dry lake to evaporate. If successful this would eliminate an average of some 400 tons of salt a day from the Pecos River downstream from the springs.

New York.—Joseph E. Upson, Mineola: In all areas in which salty water occurs in New York, the only proved encroachment has occurred on western Long Island. In other parts of the State it is either nonexistent or unmeasured.

Kings, Queens, and Nassau Counties have engaged in a long and fairly successful battle against salty water moving inland from Long Island Sound at depth in fresh-water aquifers as a result of a disruption of a Ghyben-Herzberg equilibrium. State laws passed in 1933 and 1935 provided the basis for governing the drilling of wells and the use of ground water on Long Island. Among other things, it has been required that water used for cooling purposes be returned directly into the aquifer instead of being dumped into the sewers. In addition, all public-supply wells have been abandoned in Queens County and up-State or other sources substituted. Compliance with the regulations has largely restored the water table and stopped, or even reversed, the inland movement of salt water, but a decline in salinity of the encroached-upon ground water has not been appreciable in 1954.

Ohio.—Stanley E. Norris, Columbus: Salt-water encroachment in Ohio stems entirely from improper disposal of industrial wastes.

Oklahoma.—Stuart L. Schoff, Norman: Salt-water encroachment in Oklahoma is caused chiefly by highly mineralized surface water, salt-water springs, leaky or abandoned wells that tap salt water, and improper handling and disposal of sewage wastes and oilfield brines. Not much can be done about natural contamination of fresh-water aquifers, but stricter enforcement of laws is needed. Disposal of brines in evaporation pits from the Oklahoma City oilfield and improper disposal of sewage wastes from Oklahoma City had so polluted the ground water along the North Canadian River that by 1938 the city of Shawnee, 40 miles downstream, had to abandon its municipal wells and develop a new supply. Oilfield brines from evaporation pits encroached upon the municipal well field of Cyril in 1947. Prompt action by the city forced abandonment of the pits as a means of disposal, and the well field freshened again.

Oregon.—R. C. Newcomb, Portland: Salt-water encroachment in Oregon has been of little importance. Two areas of contamination are at Salem where the disposal of ammoniated alum wastes at an aluminum plant has caused local encroachment in a fresh-water aquifer, and in some of the enclosed basins of southeastern Oregon,

where saline waters occur. By careful development, irrigators and stockmen can avoid damage.

Rhode Island.—William B. Allen, Providence: Encroachment occurs in Rhode Island in Providence and Warren, where the encroachment results from pumping which draws the water table down below the level of tidal streams nearby that contain salty water from the ocean.

South Carolina.—George E. Siple, Columbia: The most serious area of salt-water encroachment is in parts of coastal Beaufort and Jasper Counties, near the southern tip of the State. The aquifer is the Ocala limestone of Eocene age, a northern extension of one of the main members of the Floridan aquifer. Other places of encroachment, less critical, exist in the Charleston and Georgetown areas.

South Dakota.—Kenneth E. Vanlier, Huron: In areas where there is sufficient artesian head, saline waters from wells tapping the Fall River and Lakota sandstones have locally contaminated aquifers in the glacial drift. From flowing wells, the saline water seeps directly into the glacial drift or drains into ponds, where it is concentrated by evaporation before seeping into the drift. Encroachment also results from poorly constructed wells or wells with corroded and leaky casings.

Texas.—Allen G. Winslow, Austin: Areas of major salt-water encroachment in Texas are Harris County, Galveston County, the Beaumont-Port Arthur area of Jefferson County, the Winter Garden district of south Texas, and the El Paso area. In Harris County the encroachment has been more of a threat than an actuality. In Galveston County, the encroachment has been sufficient to force the curtailment of pumpage in the industrial area of Texas City. In the Beaumont-Port Arthur area, encroachment has occurred to such an extent that the estimated pumpage has been reduced to less than 1 million gallons daily in an area that formerly used 20 million gallons daily.

The contamination in the Winter Garden district has occurred largely through leaky wells that penetrate salt-water sands before reaching the principal aquifer. In the El Paso area, encroachment has been principally from salt-water sands overlying the fresh-water aquifer, but salt water also underlies the fresh water. Salt domes in Texas, unlike those in Louisiana, appear to cause little encroachment in the fresh-water aquifers they penetrate. Contamination by oilfield brines has been a much more severe problem in the past; it is now fairly well controlled.

Utah.—Herbert A. Waite and John H. Feth, Salt Lake City: Salt-water encroachment in Utah is of three main types—horizontal encroachment in a fresh-water aquifer undergoing dewatering; vertical encroachment from one aquifer to another either along natural conduits, chiefly fault planes, or through wells, and induced by artficially created hydraulic gradients; and encroachment in shallow water-table aquifers by salts resulting from irrigation-induced waterlogging.

Encroachment problems of the third category are perhaps commonest in Utah, but some areas are plagued by all three types. Horizontal encroachment into pumped fresh-water aquifers is commonest in the Salt Lake City-Ogden area and in the Bountiful district. Vertical encroachment through poorly constructed wells, wells with leaky casings, or abandoned wells is most serious in the Salt Lake Valley, at Delta and Ogden, in the Cache Valley, at Fillmore and in the Beryl-Enterprise area. Other areas are known to be afflicted but are not so critically involved. Waterlogging and attendant salt-water encroachment have ruined or greatly harmed many areas that once produced bounteous crops. The areas chiefly affected are the Cache Valley, Salt Lake Valley, Tooele Valley, Utah Valley, and smaller areas near Delta, Vernal, and Fillmore.

Virginia.—Allen Sinnott, Charlottesville: Aquifers involved in saline en-

croachment are in the broad area surrounding Hampton Roads and in limited areas elsewhere in the Coastal Plain, particularly in Spotsylvania County. The deeper aquifers involved contain residual salines from high-level, post-Cretaceous seas, chiefly Pleistocene. Except in areas where encroachment is induced by pumping, not much can be done to alleviate the situation. The investigations by J. D. Cederstrom, of the Geological Survey, in 1947 indicated that, by artificial recharge of fresh water into the salty aquifers through wells, some useful results may be attained. He injected fresh surface water into a saline aquifer and later was able to recover much of it.

West Virginia.—Charles W. Carlston, Morgantown: Salt-water encroachment is a minor problem in West Virginia. There are areas in the alluvium along the Ohio River where saline encroachment occurs, chiefly between Paden City and Waverly. In this stretch are the Sistersville, Bens Run, St. Marys, Belmont, and Waverly oilfields. Brines from the fields are the source of the encroaching salines.

Wisconsin.—William J. Drescher, Madison: Salt-water encroachment is a minor problem. Saline water is known to occur in five areas along the boundaries of the State, but encroachment as such has been known to occur only in an area in the eastern part of the State that includes parts of Brown, Calumet, Door, Kewaunee, Manitowoc, and Sheboygan Counties. The deeper wells in this area yield highly saline water, and in places where artesian wells leak or are allowed to flow unchecked their salty water encroaches upon the shallow, fresh-water aquifers.

SALT-WATER ENCROACHMENT thus looms as a big problem in some parts of the United States. Fortunately, even in the States that are seriously threatened, there generally still exist plentiful ground- and surface-water supplies that need only intelligent development and use to make them serve long-term human needs.

Salt-water encroachment, both from the ocean water and from residual saline bodies, is most serious in the coastal States. In the inland States, oilfield brines, industrial wastes, and encroaching alkali and salt waters in irrigated areas pose the most serious problems.

In places where the factors involved in salt-water encroachment are known, State and local agencies generally can formulate operational plans for the effective, continued, and satisfactory use of water. If, through ignorance, apathy, or carelessness, the proper handling of this precious resource is neglected, salt-water encroachment could become disastrous.

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Pollution—A Growing Problem of a Growing Nation

Carl E. Schwob

Water in its natural state is never 100 percent pure. Rain as it falls gathers impurities from the atmosphere. Contact with man's activities adds pollution in various forms, most of which affect the uses we can make of the water.

The principal forms of pollution are domestic wastes (sanitary sewage), industrial wastes, and silt.

Sanitary sewage includes everything that goes down the drains of a city and into its sewer system—the used water from toilets, bathtubs, and sinks and washings from restaurants, laundries, hospitals, hotels, mortuaries, and many more.

Industrial wastes are the acids, chemicals, oils, greases, and animal and vegetable matter discharged by factories, sometimes into city sewer systems and sometimes through separate outlets directly to the watercourses.

Silt is the soil that washes into the streams, muddies the waters, and fills up reservoirs.

Until comparatively modern times, the disposal of rubbish, garbage, and human wastes was a haphazard undertaking, left entirely to each household. Usually wastes were dumped in alleys, streets, or ditches for eventual destruction by time and the elements. Sewers existed even in Babylonian times, but they were used mainly for draining off excess surface waters rather than for carrying away wastes. The first record of sanitary sewers—usually natural watercourses or dug ditches—appears in the late 17th century. The modernization and general use of sewers did not develop until almost 200 years later.

The intervening years brought the Industrial Revolution, great concentrations of population in factory towns, the development of inside plumbing, and the general use of cesspools as repositories for human wastes. Disease epidemics, traced to pollution of wells by seepage from the early cesspools, provided the impetus about the middle of the 19th century or so for the first systematic construction of our sewer systems.

With the widespread adoption of modern sewer systems, which collected the wastes of whole cities and discharged them at a few concentrated outlets, human wastes and other filth no longer accumulated in the streets to make pestholes of our cities. But the problem had only moved its location. The many communities taking their water supplies from lakes and streams were still menaced by the wastes reaching those surface waters through sewer outlets. Science provided a solution by developing purification processes for removing bacteria and other pollutants from water.

Municipal water purification systems have remained a remarkably effective protection against the health hazards of water pollution up to the present day. But the growth and concentration of population and the increase in the volume of pollution make more complicated and costly the job of producing safe and acceptable drinking water. The dangers increase. A human error or a mechanical failure that permits even a small break in the protective wall can bring disaster.

Serious as are the dangers from the wastes discharged by municipal sewers, they are only part—and in point of complexity only a small part—of the total pollution problem that the Nation faces today. The sevenfold increase in industrial production since 1900 has added tremendous volumes of wastes to the streams. The new products that advancing technology is turning out in infinite variety and with astonishing rapidity have created complex problems of water pollution. The possible effects of some of the wastes stemming from production and widespread use of the new chemical products are not yet

known. The effectiveness of present water-treatment processes in removing them is not fully assured.

Most uses of water are affected by pollution. We all believe that water for drinking and related domestic purposes has highest priority and that those uses must be safeguarded from the effects of pollution.

Water is the most used raw material in our factories. Most of it is taken from rivers and lakes. For many industrial processes, the water must be relatively pure. The fast-growing synthetic and chemical industries require tremendous amounts of good water. The steel industry alone uses 13 billion gallons a day. It takes 365,000 gallons to produce a ton of rayon yarn; about one-half million gallons for a thousand yards of woolen cloth; more than a million gallons for a thousand barrels of aviation gasoline. Production costs rise if the water must be treated before it is used. The availability of good-quality water therefore is an important matter in the location of new industrial plants. Its lack discourages new industry and the expansion of existing plants and adversely affects the overall economy of the region.

Crops irrigated by waters containing sewage pollution may transmit disease. Waters carrying industrial pollution, such as chemical wastes, can damage the crops they irrigate. The increase in use of supplemental irrigation in the East has raised questions of quality of water. Many natural streams formerly relied on to provide water for livestock have become so polluted that their continued use is unsafe.

Desirable fish do not thrive in heavily polluted waters. Shad have almost disappeared from some of the rivers in the East. In one western valley the annual salmon catch, once valued at 5 million dollars, dropped a few years ago to about 1 million dollars. An intensive pollution abatement program in the area is now improving stream conditions, and salmon are returning. Large areas of shellfish-producing waters have been closed because of the dangers of pollution.

Outdoor recreation suffers from pollution's damaging effects. Beaches have been closed to swimmers because of health hazards. Boating not only loses its esthetic appeal when waters are loaded with pollution; it becomes actually dangerous. The joys of waterside picnicking and camping are destroyed. Sport fishing produces few pleasures and fewer fish. Substantial economic loss is suffered by the recreation industry, which is an important source of income in many States.

Pollution can be controlled. Pollution is not something that must be endured as an inevitable consequence of our urban and industrial growth. Remedies already available will prevent much of it. Some difficult problems remain, but they can be solved.

We have many examples of the dramatic success that can be achieved with presently known methods of controlling pollution.

Pennsylvania's clean-streams program in a few years has returned the Schuylkill River to a semblance of what it was before the days of heavy industrial pollution. Game fish are thriving in the upstream pools, bathing and boating have regained their popularity as river sports, and riverfront real estate has risen in value. Other Pennsylvania streams are showing similar improvement.

A large-scale, basinwide program initiated several years ago in Kansas has substantially reduced the heavy bacterial pollution that was threatening the water supplies of communities along the Kansas River.

The eight States of the Ohio River Basin, working together and with the cities and industries of the area, succeeded in 5 years in reversing the pollution trend of half a century. New stream pollution has been curbed, and existing pollution is being reduced in a program designed to protect the health and economic well-being of one of the country's major industrial areas.

Another cooperative interstate program is restoring waters of the Delaware River to their maximum usefulness. The goal was the elimination by 1955 of all pollution discharges that do not meet established requirements.

The Willamette River in Oregon, mistreated for many years, by the late 1930's in certain stretches had become little more than an open sewer. Legislation adopted in 1939 gave authority for a cleanup program. As a result, the water can be used for industrial and domestic purposes, for the propagation of salmon, and for most recreational purposes.

Water can purify itself up to a point, by natural processes, but there is a limit to the pollution load that a stream can handle. Self-purification, a complicated process, is brought about by a combination of physical, chemical, and biological factors. The process is the same in all bodies of water, but its intensity is governed by varying environmental conditions.

The time required for self-purification is governed by the degree of pollution and the character of the stream. In a large stream, many days of flow may be required for a partial purification. In clean, flowing streams, the water is usually saturated with dissolved oxygen, absorbed from the atmosphere and given off by green water plants. The solids of sewage and other wastes are dispersed when they enter the stream and eventually settle. Bacteria in the water and in the wastes themselves begin the process of breaking down the unstable wastes. The process uses up the dissolved oxygen in the water, upon which fish and other aquatic life also depend.

Streams offset the reduction of dissolved oxygen by absorbing it from the air and from oxygen-producing aquatic plants. This replenishment permits the bacteria to continue working on the wastes and the purification process to advance. Replenishment takes place rapidly in a swiftly flowing, turbulent stream because waves provide greater surface areas through which oxygen can be absorbed. Relatively motionless ponds or deep, sluggish streams require more time to renew depleted oxygen.

When large volumes of wastes are discharged into a stream, the water becomes murky. Sunlight no longer penetrates to the water plants, which normally contribute to the oxygen supply through photosynthesis, and the plants die. If the volume of pollution, in relation to the amount of water in the stream and the speed of flow, is so great that the bacteria use the oxygen more rapidly than reaeration occurs, only putrifying types of the bacteria can survive, and the natural process of self-purification is slowed. So the stream becomes foul smelling and looks greasy. Fish and other aquatic life disappear.

Those conditions are evidence of the need for pollution abatement measures that will reduce the volume of wastes discharged to the waterway to an amount well within the self-purification capacities of the stream.

Determination of this safe amount involves several factors, which may vary for different streams and even for separate reaches of the same stream—streamflow, chemical characteristics, temperature, quality demands of downstream water uses, time and distance between discharge point and next point of use, and the like.

Sewage treatment brings about the required reduction in the pollutional effect of sewage wastes before they are discharged into the watercourses. For industrial wastes, combinations of treatment, inplant process changes, and recovery of materials for reuse are utilized.

There are various degrees of sewage treatment. In primary treatment, which removes about 35 percent of the pollution load of sewage waters, the sewage first passes through a screen, which catches large objects, such as sticks and rags. Next the water flows slowly through a grit chamber, allowing sand, gravel, and other heavy

objects to settle. The water then flows into a large settling tank, where it stands for an hour or more. The solids in the waste matter settle to the bottom as sludge or rise to the top as scum. The water between the two layers is then drained off. If only primary treatment is necessary, the water is chlorinated to kill bacteria and is then discharged to the stream. The settled sludge is removed to a digestion tank or drying beds, where it is made harmless. It may then be used for fertilizer, soil conditioner, or landfill, or it may be burned.

If a greater reduction in polluting materials is required, the waste water from the primary settling tank is sprayed on a bed of coarse stones. A bed is usually about 6 feet deep. As the liquid trickles through it, bacteria and biological growths, which coat the stones, catch the suspended and dissolved materials and remove from them the food they need. The suspended and dissolved materials thus are transformed into more elementary material, much of which can be removed by settling. In some places the activated sludge process, which also depends on the action of bacteria, is used instead of the trickling filter. As an added precaution, the effluent from the treatment plant may be chlorinated to destroy the disease-producing bacteria. Varying degrees of pollution reduction, up to practically 100 percent, may be achieved by an intensification of all these secondary treatment processes.

The determination of the degree of treatment needed before sewage or organic industrial wastes are discharged to the watercourses is a complex and technical question. If it were possible to standardize treatment requirements at the highest level—complete removal of all harmful wastes—the complexities might be avoided—but the economics of the situation precludes this simple solution. The higher the degree of treatment, the more costly it becomes. For example, the treatment facilities required to achieve 35 percent reduction in the pollution effect of sewage (primary treatment) cost about 35 dollars per capita; those for 75 percent reduction cost about 70 dollars per capita; and for 90 percent reduction, about 110 dollars per capita. Thus the cost—$40—of the 15 percent additional reduction between 75 percent and 90 percent is greater than the cost of the initial reduction of 35 percent. The estimates of course are general averages; actual costs for individual communities depend on many factors and may vary widely.

In setting requirements of treatment, therefore, the matter of economics must be given due weight, along with such other considerations as the quality standards required for downstream water uses, the degree of pollution reduction provided through the natural stream purification processes, and the particular requirements inherent in the water rights law of the area.

Research on the health-related aspects of pollution was begun in the United States late in the 19th century.

The work of Pasteur, Koch, and Lister had established that certain types of disease, such as typhoid fever and cholera, were transmitted through polluted water. That knowledge was the foundation for the development of methods for removing harmful bacteria from sewage before its discharge into the watercourses.

Pioneer work was done by the Lawrence Experiment Station of the Massachusetts State Health Department, established in 1886. Field studies were undertaken by the Public Health Service about 1910 in cities of the Great Lakes region to determine the relation of sewage-polluted drinking water supplies to the prevalence of typhoid fever and other waterborne diseases. Other early investigations covered international waters between the United States and Canada, the Potomac River (with special reference to contamination of shellfish), the Missouri River, and the Illinois, Scioto, and Ohio Rivers (with special attention to de-

velopment of knowledge on natural purification phenomena). In 1938 the first full-scale investigation to develop an overall pollution control plan and program for a major river basin (the Ohio) was initiated, in cooperation with the Corps of Engineers.

The extension of the development of comprehensive, nationwide pollution control plans was provided for in the Federal Water Pollution Control Act, adopted in 1948. The development of these blueprints for action involves a compilation of data on pollution sources, quantities, and characteristics; agreement on desired water uses; establishment of standards of quality for the desired uses; and finally, determination of treatment requirements to preserve the quality for those uses.

POLLUTION SOURCES numbering 22,200 were revealed upon completion of the initial data-collection phase of the State-Federal program in 1950—11,800 municipal sewer systems and 10,400 independent factory-waste outlets.

Of the 92 million people served by sewer systems, only 54.5 million were also provided with sewage treatment (6,700 plants). Of the 10,400 industries having waste outlets separate from municipal sewer systems, about 2,600 provided treatment, 3,700 had no treatment works, and the facilities of the remaining 4,100 were undetermined. Despite the reduction of pollution by the 9,300 treatment plants, untreated or inadequately treated organic sewage and wastes equivalent to those from a population of more than 150 million were still discharged into rivers and lakes.

More than 2,000 industries discharged inorganic wastes, such as acids and poisonous chemicals, which are not measurable on a population-equivalent basis. For about 3,000 other industries, the type of waste, organic or inorganic, had not been determined. Finally, drainage from abandoned coal mines contributed an estimated 10,000 tons of acid pollution each day to the waterways.

On the basis of the preliminary data, it was estimated that new sewage treatment plants, or major additions, enlargements, or replacements of the existing plants, were required at 6,600 locations. The total cost of the needed projects was estimated at about 2.5 billion dollars. It was further estimated that each year's new needs resulting from population increases, the trend toward urbanization, and the growing factor of plant obsolescence would require construction expenditures of approximately 200 million dollars.

Thus, in order to take care of current needs and eliminate the backlog, municipal expenditures at a rate that ranges from 450 million to 500 million dollars annually would be required over a period of 10 years. This rate is much greater than has ever been attained for construction of this type, even during the peak period of the late 1930's, when the national public works program greatly stimulated construction activities to cope with sewage problems.

In 1950 it was estimated that 3,500 projects would be needed to treat industrial wastes equal to or somewhat greater in magnitude than the municipal backlog. Currently developing needs, because of industrial expansion, also were expected to require annual expenditures at least as great as those estimated for new municipal needs.

Because expenditures for industrial pollution-abatement facilities are not readily separable from total industrial construction figures, full data are not available as to the rate of progress in controlling this type of pollution. Scattered and incomplete reports indicate that the larger industries particularly are making substantial expenditures for construction of waste-treatment plants and adoption of other abatement measures. For example, industries in and near Houston, Tex., have spent about 7 million dollars for measures to control water pollution during the past few years. About a third of the industries near the Niagara

River spent more than 7 million dollars for similar measures between 1950 and 1954. The Manufacturing Chemists Association reported that the chemical industry alone was spending about 40 million dollars a year for research on air and water pollution and corrective measures. A representative of a large automobile manufacturer stated that his firm spent 32 million dollars over an undisclosed period for similar research and abatement measures.

Nevertheless, evidences of worsening pollution conditions in many areas proves that the construction of treatment plants for industrial wastes is lagging behind needs.

Water laws of the different States vary widely, but legal decisions under them consistently support the right of the riparian owners to be protected against pollution. In areas governed by the common-law doctrine, each riparian owner has the right to have the stream that flows past his property unimpaired in quality and undiminished in quantity. In States where the reasonable-use doctrine is in force, the reasonable use of a stream by a riparian owner may not be interfered with. In western areas governed by the prior-appropriation doctrine, recognition is given to the accepted rule that the acquisition of water by prior appropriation for a beneficial use is entitled to protection.

Responsibility for pollution abatement for the protection of water resources is shared by local, State, and Federal agencies. Under the American tradition of community responsibility, each city and industry has a clear obligation to construct, operate, and maintain all the pollution-abatement works necessary to assure that its wastes will not cause harm to others.

The States administer the regulatory provisions of their laws to control pollution and conduct State programs, which include investigations, development of coordinated plans, establishment of standards of water quality and waste treatment requirements, and assistance to local efforts to promote public support of needed waste-treatment facilities.

State agencies provide review and approval by engineers of construction plans for installation and extension of public sewer systems and treatment plants, inspection of plant operation, provision of laboratory services to determine adequacy of treatment, and the licensing or certification of operators of sewage works. Many States have standards for the design, construction, operation, and maintenance of sewer systems and treatment plants. In 30 States, the State pollution control authority operates within the State health department. In 9 others, the health department is the executive agency of a board or commission. In 9 States, the health department is represented on the official water resources or water pollution control agency.

At least 7 States provide some financial help to municipalities in planning or constructing sewage treatment plants. Pennsylvania, for example, enacted a law that provides that, beginning in 1954, municipalities that have constructed sewage treatment facilities since 1937 may receive reimbursement from State appropriations at a rate of 2 percent of the cost of the facilities each year for 50 years. Pennsylvania also makes grants-in-aid available to cities to help defray the cost of preparing plans for treatment works.

The federal responsibilities are primarily of a supporting nature, designed to assist and strengthen State programs. They include research, technical assistance on particularly difficult problems requiring highly specialized personnel or other resources not always available to individual State agencies, promotion of coordinated interstate action, and limited enforcement on interstate pollution problems.

The Federal Water Pollution Control Act of 1948 established the principle of limited Federal assistance to municipalities for the planning and

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the construction of sewage treatment plants, by authorizing annual appropriations of 1 million dollars for planning grants and 22.5 million dollars for construction loans. No such grants or loans have been made however, as the Congress has made no appropriation of funds for the purpose.

Under the Federal Act, cooperative State-Federal development of comprehensive programs has progressed to the point that preliminary data have been published for all of the Nation's river basins. Completed comprehensive programs have been adopted by the Surgeon General and are being put into practice by the State agencies in 14 drainage basins, including the entire Missouri River System, most of the Upper Mississippi Basin, the Central Columbia Basin, and others. Other comprehensive programs were in various stages of development. Adoption of a comprehensive program does not in itself reduce pollution, but it does give the citizens of the river basin—city officials, industrial leaders, the farmers, fishermen, conservationists, and others—a blueprint, based on good engineering practice and sound economics, of their specific responsibilities in relation to the overall problem and to the responsibilities of their upstream and downstream neighbors.

Improved interstate cooperation has been achieved through interstate compacts. Five such, dealing with the Ohio, Potomac, and Delaware Rivers, the waters of New England, and the interstate waters in the New York City area, were in operation in 1954. In some areas, regional pollution control councils have been formed as a preparatory step toward formal compacts. Among the noteworthy achievements of the councils has been the agreement on standards of water quality reached by the 10 States in the Missouri Basin and by the 4 States in the Pacific Northwest. The interstate compact groups and councils provide a means for coordinated action on pollution control for almost every area of the entire country.

Interstate cooperation has been further aided by the adoption of new water pollution control legislation or amendments to existing legislation by more than half the States since 1948. The improved legislation, incorporating the basic principles set forth in a model State law developed by the Public Health Service, has resulted in stronger State programs that have a more uniform and consistent approach to the pollution problem.

THE COMMUNITY RESPONSIBILITY for building needed treatment works can best be fulfilled through the informed action of local citizens. Facts on pollution problems and needs must be brought to the attention of the public.

Obtaining the best treatment for the least cost requires the professional guidance of engineers, lawyers, and experts in municipal finance. Engineers design the treatment works to meet specific local needs, supervise the letting of contracts and the construction, and train the plant operator. Legal aid is necessary to insure clear property titles, compliance with State and local laws, and legal financing procedures. The most frequently used methods of obtaining revenue are through general property taxes, special assessments, and service charges. Combinations of the methods are often employed. Another possibility, legally permissible in many States, is the formation of a sanitary district or authority composed of all or part of a number of neighboring communities.

FASTER PROGRESS is needed with respect to some phases of the problem, despite the accomplishments of local, State, and Federal programs.

Construction of pollution-abatement works, municipal and industrial, is lagging behind the increasing volumes of waste. Much of the State and Federal effort of the past few years has been directed toward producing the foundation material necessary to a good construction program. Efforts must now be marshaled for a sustained

drive to raise construction levels to meet the needs.

Research has failed to keep up with the new problems created by advancing technology and changing water patterns. Greater emphasis is required in many areas of research in order to permit more rapid and effective control measures. Some of the problems urgently needing special attention are:

The impact on public health of increased bacterial, virus, and chemical pollution, and the ability of present processes to cope with increased volumes and new types of pollution;

A redefinition of the natural purification phenomena of streams in the light of the new composition of wastes including chemical loadings;

The development of more economical waste treatment methods—success in this area would save millions of dollars of treatment plant construction cost;

Adjustment of laboratory techniques for measuring pollution levels in streams and for determining efficiency of water treatment;

The effect of impoundments on pollution behavior in streams;

An infinite number of new problems associated with the pollution of streams by radioactive materials.

MORE EFFECTIVE INTEGRATION of comprehensive plans to control water pollution with overall programs to develop water resources is essential in order to assure full consideration of the effects on public health of stream regulation through the construction of projects for flood control, navigation, power, and irrigation, or combinations of them. Pollution-abatement works are designed with consideration to the streamflow conditions that exist in the watercourses into which they drain. The governing standard as to the type of treatment to be constructed is the low-flow record of the watercourse. The change in characteristics of streamflow resulting from the construction and operation of stream-regulating devices can seriously alter the effectiveness of waste treatment facilities, thus negating the public health benefits to be derived as well as the beneficial effect that adequate dilution water provides for all water uses.

Through consideration of these factors in the early planning stages of water projects, design adjustments can often be made that will avoid the difficulties and lose none of the benefits of stream regulation.

The continued usefulness of our streams will depend on our desire and ability to control pollution. There will be an ever-increasing demand for clean water. Only by reclaiming and reusing water that has already been used for one or more of its myriad purposes can we meet these growing demands. We cannot escape the fact that unless pollution is controlled, the Nation's health and economy will suffer greatly.

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Treating Waste Water for Cities and Industries

Ralph E. Fuhrman

The use of water by individuals and industries usually imparts qualities to it that make it unfit for further use without some processing or time for natural purification or both.

Essentially the same volumes of water used in cities and by industries apply to waste waters, except in industries that may happen to have a high consumptive use of water. The quantities of domestic sewage may vary from 70 percent to 130 percent of the quantities of water, depending on the character of the use, the ground-water level, and the tightness of the pipe systems. With perfect tightness, unattainable in practice, the liquid waste of any community would practically equal the water supplied.

The extensive system of pipes in public property necessary to serve each private property with water is duplicated by a pipe system to receive the used water from each property. The sewer system is the counterpart of the water system. Both are necessary to the community for the full enjoyment of the benefits of a public water supply. The systems are joined in our homes by plumbing fixtures. The same general relations hold in industrial uses.

The authority collecting the community's liquid wastes assumes the obligation of proper disposal of such wastes. The volume requires that the wastes be returned to a body of water, although in arid regions discharge on the ground may be practiced for irrigation. Improper disposal may cause stream pollution, with possible jeopardy to the life in and near the stream, degradation of quality of downstream water supplies, and nuisance and offense to sight and smell.

The problem in most places is considered one of the disposal of sewage into a watercourse and any needed treatment of the wastes before discharge to reduce to a proper level the load of polluting material on the receiving body of water.

Domestic sewage is ordinarily more than 99.9 percent water. Even a considerable part of the remaining 0.1 percent (1,000 parts per million by weight) is the same mineral matter that was originally present in the water. The increase in solid content because of use actually is only a few hundred parts per million, but it is the nature of the added material, rather than its amount, that may make treatment necessary.

The material is made up of the chemically complex organic and mineral wastes of living. Among them are many bacteria, some of which may produce disease. The total number of bacteria a person adds each day is about 100 billion. No definite relationship exists between harmless bacteria and the small proportion of disease producers in the total. Because the dangerous ones may occur at any time, sewage must always be considered potentially dangerous. Any parasite hazardous to man is certain to find its way into his used water supply.

PROMPT REMOVAL of the wastes by the water system is essential in modern living. Safe plumbing is needed within buildings to maintain health protection. The sewer system continues that protection on a communitywide basis. Waterborne diseases are controlled to a large extent by this combination of handling waste water and properly treated public water supplies. Breaking the route of infection between waste water and the public water supply aids greatly in the reduction of typhoid and paratyphoid fevers, amoebic and bacillary dysentery, and cholera.

Ultimately the receiving watercourse, through natural self-purification, will be returned to its normal state of cleanliness. The process of sewage disposal cannot be considered complete until that point is reached. Disease might

be transmitted through shellfish or watercress harvested from polluted waters; through garden produce that has been irrigated by sewage or polluted water or that has been fertilized by sewage sludge containing harmful organisms; through contaminated soil or by flies carrying contamination to good soil; or through bathing or incidental contact with polluted water along shore or in watercraft.

State-by-state control of water pollution is vested in the State health department or a board with representatives of the State departments concerned with health, water conservation, and industrial development. Control is exercised by requiring approval of waste-treatment works before construction and requiring effective operation of such works. Periodic inspections of plants and receiving waters are made to check continuing adequacy of the facilities.

Interstate problems are attacked by several organizations in the United States. Because water pollution does not follow State boundaries, groups within a drainage basin provide a means for close collaboration. Typical of such organizations are the Ohio River Water Sanitation Commission, which comprises the Ohio Basin except the part previously organized as the Tennessee Valley Authority; the Interstate Sanitation Commission, serving Greater New York City; the Interstate Commission on the Delaware River Basin; and the Interstate Commission on the Potomac River Basin. On a national basis, the Water Pollution Control Division of the United States Public Health Service gives help primarily through reports and research. This work, originally authorized by Public Law 845, 80th Congress, cooperates with State agencies in furthering activities to control stream pollution.

The discharge of domestic sewage into a watercourse provides the environment for decomposition of the various chemical products in sewage. The nitrogenous compounds in the dead organic matter decompose to nitrogen in the form of ammonia (NH_3). Under aerobic conditions, oxidation proceeds to convert the ammonia to nitrate nitrogen (NO_3), the form in which the nitrogen is recognized as plant food and a common constituent of fertilizer. When it is taken up by plants, it is incorporated as plant protein. If it is consumed by an animal, animal proteins are formed. By excretion or death of the animal, the cycle is started again. Similarly, carbonaceous material oxidizes to carbon dioxide and is then available for living plant matter. Sulfurous compounds likewise are decomposed to hydrogen sulfide and, by further oxidation, to sulfur and sulfates. In that form sulfur may be taken up by plants.

In all of these cycles the atmosphere is the great reservoir of oxygen, nitrogen, and carbon dioxide, but at the same time those gases will be available dissolved in the water. Because of the most important role of oxygen to the overall decomposition process, the content of oxygen is critically important to the condition of the water. If aerobic conditions are not maintained, putrefaction will occur and produce foul odors and general nuisance.

The amount of dissolved oxygen in the water—its most important characteristic—is a major standard of the quantity of the polluting material or oxygen-demanding constituents that may be discharged into a watercourse.

The allowable loading is then determined from the quantity and oxygen demand of the sewage. From this information the possible need of treatment is determined.

Efficiencies of three common sewage treatment processes, expressed in percentage of removal of oxygen demand, are: Plain sedimentation, 25 to 40 percent; plain sedimentation, plus trickling filtration and secondary sedimentation, 80 to 95 percent; and activated sludge, 70 to 95 percent.

The values given depend on good

operation of the plants and adequate provision for related processes, such as sludge digestion or other means of sludge treatment. For example, a community of 100,000 persons has a stream available to receive its sewage. If the stream can assimilate the sewage of only 25,000, it would be necessary to employ trickling filter or activated sludge treatment to accomplish a reduction in oxygen-demanding constituents for a population equivalent of 75 percent. But if the same community had a stream capable of assimilating the sewage of 75,000 persons, the required reduction by treatment would be only 25 percent.

Plain sedimentation, cheaper than the biological treatment units, would be adequate in that case. Plain sedimentation often is designated as primary treatment, and complete treatment denotes primary treatment plus secondary treatment.

Included in sewage treatment methods are screening devices for the removal of suspended solids, such as rags, sticks, and other trash in the sewage; the removal of grit by rapid sedimentation in grit chambers or detritus tanks; and the removal of floating solids by skimming tanks or from settling units.

The fine suspended material, not removed by screens or grit chambers, is subjected to sedimentation. Tanks for the purpose must have suitable means for the removal of settled sludge from the tank bottom. That may be accomplished mechanically or by specially designed tank bottoms of hopper construction. Small installations that serve only a few hundred persons may use a septic tank, which combines the processes of sedimentation and sludge digestion with limited success. Far superior to the septic tank is the Imhoff tank, which combines the processes of sewage sedimentation with sludge digestion in a single structure but is so arranged that no interference between them occurs. Such tanks may well be employed for installations serving several thousand persons.

Secondary treatment methods, which are essentially biological oxidation units, frequently consist of trickling filters.

Such filters are basins 3 to 6 feet deep and filled with gravel, stone, cinders, slag, or vitrified clay forms, made specially for the purpose. The settled sewage is applied to the filter surface through fixed nozzles at the surface of the bed or by a rotary nozzled pipe distributor.

In either case, the trickling of the settled sewage over the stones brings about intimate contact between the organisms that naturally thrive in the slimy growths on the stones, the oxygen, and the organic material dissolved or finely suspended in the applied sewage. The resulting oxidation converts much of the organic matter to a form in which it can settle and which is removed by the secondary sedimentation process. Recirculating the filter effluent through the unit to increase the supply of organisms and oxygen is a common practice. The result is a higher efficiency per unit volume of the filter medium.

Oxidation of the sewage solids by activated sludge is achieved in tanks, usually 15 feet deep, through which the sewage flows for 1.5 to 6 hours or more. During that time compressed air is released at the bottom of the aeration tank in order to provide an abundant supply of oxygen and suitable agitation to the tank contents. The sludge so produced is removed by secondary sedimentation and a part of it returned to the process at the aeration tank inlet in order to provide a plentiful supply of organisms as well as a large surface for the absorption of incoming solids.

Large, shallow oxidation ponds may be employed as a secondary treatment or (in some localities) as the whole treatment. Their oxidizing effect depends on absorption of oxygen from the atmosphere and, to a much smaller extent, the production of oxygen by water plants. In arid regions, such ponds may consist of the entire treatment process; they are economical and

they provide a sanctuary for waterfowl.

Sedimentation tanks are used to remove matter that will settle naturally. The settled sludge is largely the concentrate of the solids in the sewage and therefore must be treated to prepare it for safe nuisance-free disposal.

The most common practice in the treatment of municipal sewage is digestion. Digestion consists of holding the sludge in enclosed, sometimes heated, tanks for 30 days or more. Light and air are excluded, and completely anaerobic conditions are so achieved. Under the proper controls, the solids will be decomposed by bacterial action into simple, inoffensive compounds. The sludge is partly liquefied and partly gasified, and it therefore loses its offensiveness. It will drain and dry readily on drying beds, which are shallow basins with an underdrained sand floor. In larger communities the sludge may be dewatered by rotary vacuum filters and sometimes further processed by heat drying.

A sludge gas, consisting of about 60 percent methane, is produced during digestion. The usual quantities may amount to 0.75 to 1.0 cubic feet a person a day. The heat available in this fuel, amounting to about 500 British thermal units a person daily, may be used in a plant to heat space or water, for laboratory burners and incinerators, for screenings or sludge, and (in the larger plants) for internal combustion engines that produce electricity through generators or by direct operation of large mechanical units, such as pumps or air compressors.

Digested sludge is generally available for agricultural use after drying. Sometimes loosely termed "fertilizer," it is often considered a soil conditioner because its humus content is approximately 50 percent of the dry solids. On a dry basis, the nitrogen content in the form of nitrates may be about 2 percent in digested primary sludge to 6 percent in activated sludge. The content of phosphoric acid and potash often is about 1 percent. The phosphoric acid has been increasing in municipal sewage by the phosphorous in some synthetic detergents.

Some cities sell the sludge, but the income does not approach the overall cost of sewage treatment. It is a satisfactory method of sludge disposal, however, because it returns elements essential to the growth of plants to the soil.

WATER-CARRIED INDUSTRIAL WASTES have many constituents, seemingly as varied as the industrial products themselves and the substances entering into their manufacture. Large volumes of water are used for cooling purposes only, and their undesirable contribution to the stream is elevation of temperature. If that is great enough to upset the normal biological life of the stream, it may become necessary to dissipate the heat before discharge.

Processes of washing, flushing, extracting, impregnating, chemical treatment, and other operations may impart to the water qualities inconsistent with good stream sanitation. Waste containing toxic ions or chemicals may destroy the biological life necessary to the self-purification of a stream or of the proper functioning of waste-treatment processes.

Organic chemicals, oils, dyes, and floating solids present special problems.

The problem of treating industrial waste water should be attacked first in the industrial plant. Every reasonable effort should be made to reduce water-carried waste by choosing or changing the manufacturing process to reduce the volume and concentration of the wastes. Other means include the recovery of byproducts from the waste and recycling water to achieve maximum conservation. Only after those approaches have been explored should discharge of the waste into a municipal sewer system or into the company's industrial waste water treatment plant be considered. Additional care may be required within the factory to achieve those results. Spillage of material ultimately flushed into the sewer should

be kept to minimum. Washing of utensils, equipment, and the floor should likewise be accomplished with a minimum of water.

The discharge of municipal wastes into the municipal sewer is convenient because (once the wastes are delivered to the sewer) responsibility for handling, treating, and disposing of them becomes that of the municipality. Often the volume of industrial waste is so small that it is scarcely noticeable, but it might seriously damage the sewer system or the treatment plant if its nature is overlooked. The authority owning and operating the sewer system must control the discharge of industrial waste waters and require their exclusion from the sewer or any necessary pretreatment before they are discharged into the sewer.

Methods of treating industrial waste water include those commonly used on domestic sewage. Often it is neutralized to make the wastes suitable for treatment. Equalizing tanks frequently are used to receive wastes as produced and discharge them at a nearly equal rate to avoid shock loads on treatment facilities.

A few examples will indicate the varying nature of industrial waste waters and the accepted methods of treatment.

Milk wastes include the washings from cans, bottles, and tanks, and whey and buttermilk originating in dairies, creameries, milk drying plants, and cheese plants. As no benefit and possibly some detriment results from sedimentation, the usual treatment is by trickling filters directly. Whey is offered to farmers for hog feed to reduce the treatment problem and save waste. Laundry wastes are often treated successfully by direct treatment on trickling filters. Cannery waste may include toxic chemicals, such as sulfides and chromates.

Equalizing tanks often are used to minimize batch discharges. After equalizing, the waste responds to processes applied to domestic sewage. Wastes from paper mills contain much fiber and spent chemicals. An important byproduct, activated carbon, used mainly in water purification, was developed about 30 years ago from material that was formerly wasted.

The newest addition to industrial waste water is from establishments working with radioactive materials. Because the rate of radioactivity of the materials can be neither accelerated nor delayed, the only treatment methods consist of concentrating the waste by coagulation or evaporation and storing it under control until the level of radioactivity is safe. For materials that take a long time, dumping at sea is the best method we know.

The sanitary sewer systems of most American cities have developed along with the cities themselves. Many were installed at costs below those of today. Present costs of sanitary sewer construction are about 35 dollars a person for the first installation cost. The cost is much higher in a small community than in a large one, as the small community may require 3 miles of sewer line to serve 1,000 persons, and 1 mile might be enough in the largest cities. Besides, the cost of constructing a primary sewage treatment works, if necessary, would be 4 to 8 dollars a person, and operating costs might be 30 to 50 cents a person a year. If trickling filters are employed, the first cost may be 10 to 30 dollars a person and annual operating costs from 0.75 to 1.25 dollars a person a year. Similarly, for an activated sludge treatment plant, the installed cost may be from 8 to 25 dollars a person a year and the operating cost 1.50 to 4 dollars. In all instances the higher cost is in smaller communities.

Most municipal sewer systems have grown with little regard to the overall problems of financing as the eventual requirements of maintenance repair and relief lines become necessary. In recent years the pressure of rising costs and the general public demand for cleaner streams have forced cities to

develop adequate means of financing such facilities.

Realizing the singular nature of water and sewer services to the householder, many cities have changed the water bill to a water and sewage bill to provide funds necessary to meet expenses of the sewer system. Other measures, such as the number and type of plumbing fixtures or the number of bedrooms in the house, have been used as a basis for charging for sewer service. Adding a percentage to the water bill makes billing and collection easier and is equitable. In most modern applications of the sewer service charge, the initial investment of the common or service sewer is paid by an assessment against the abutting property. The sewer service charge then provides the funds necessary for construction of main sewers, trunk sewers, outfall sewers, and, if necessary, treatment works. Such a method of financing, soundly administered, puts the sewer system on a utility financing basis, which allows it to render the service demanded by the taxpayer.

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The Problems That Face Our Cities

Harry E. Jordan

The first American public water system of which we have an authentic record is that of the Water Works Company of Boston, which in 1652 provided a supply for domestic consumption and fire protection to the residents of a single neighborhood—Conduit Street.

Almost a century later the first supply designed to serve an entire community came into being. A farmer named Schaeffer piped a supply from a spring on his farm down the main street of the Pennsylvania village now known as Schaefferstown.

At Bethlehem, Pa., in 1754, Hans Christiansen, who was an immigrant millwright, began work on the first pumped public waterworks, which was put in regular operation in 1755. The supply provided at Winchester, Va., in 1799 appears to have been the first complete works developed as a public enterprise. Seventeen cities were served by public waterworks in 1800 and 83 at the end of 1850.

In operation in 1900 were 3,300 waterworks. In 1950 approximately 17,000 communities were served by public systems.

NEARLY ALL the early works consisted of a short pipeline that brought water from a nearby spring or stream by gravity. Generally there was no storage other than that provided by the intake or diversion works. The bored wood or lead pipe employed had such small capacity that only the most meager domestic needs of the consumers were met, and little provision was made for fire protection. The later introduction of cast iron pipe, first imported from England, made possible larger lines that could carry the required volumes of water.

Before the middle of the 19th century, masonry aqueducts were laid on the hydraulic gradeline from New York's Croton and Boston's Cochituate reservoirs. Other cities used pipes of wood staves, wrought iron, or cement-mortar, which were coated in the trench.

Another advance in the first two centuries was the reciprocating steam pump, which was developed into the familiar, high-duty, cross-compound horizontal pumps and huge vertical triple-expansion pumps. The centrifugal pump, smaller in size but higher in speed than the reciprocating pump of equal capacity, entered into competition first as a low-lift device. It has

been so perfected during the past half century that it can be furnished to meet any head-capacity requirement and give dependable high-duty service.

The centrifugal pump, of either the horizontal or deep-well turbine type, with steam-turbine or electric-motor drive and often with internal-combustion engine standby drive, is now almost universally used for water-pumping installations.

POUGHKEEPSIE, N. Y., in 1870 built the first slow sand filter plant, designed in accordance with English practice. Within 20 years the earliest mechanical, or rapid sand, filters were installed, and by the end of the century ten times as many of these American-type filters were in service as the slow sand type.

In service in 1925 were 587 rapid sand and 47 slow sand filter plants, with a total rated capacity of about 5 billion gallons a day.

Other types of water treatment came into use, so that, by 1948, treatment plants of all kinds numbered 6,986, according to a publication of the Public Health Service, *Statistical Summary of Water Supply and Treatment Practices in the United States*, which was published in 1952. The plants produced more than 8 billion gallons of safe water a day.

Disinfection was used in 6,137 plants, which served more than 80,600,000 persons. Liquid chlorine was used in the largest number of installations and served the largest percentage of population.

Today, in American cities, one person in about 100,000 dies of typhoid fever each year—nearly 100 deaths a year for each 100,000 of population occurred at the turn of the century.

Two-thirds of the Nation's population is now served by public waterworks systems through about 25 million customer accounts. That service, which involves well-supervised production and distribution of safe water, must be given some of the credit for all but wiping out the scourge of typhoid fever of 50 years ago and for virtually eliminating epidemics of waterborne dysentery.

OF THE 16,747 communities in the United States served by water supplies in 1948, almost 65 percent—most of them of less than 5,000 population—were served by ground sources and 29.6 percent—mostly large communities—were served by surface supplies. The remainder received water from both ground and surface sources. Nationally, 54.2 percent of the communities received treated water; more than 43 percent were served by untreated supplies. The rest received water from both treated and untreated supplies.

Considering population served, the largest percentage, 54.6, received water from surface sources, and 79.6 percent of the total population served received untreated water as the sole supply.

There were 6,986 water-treatment plants, serving more than 83,250,000 persons, in the United States in 1948. Simple disinfection plants were the largest single type. Also, the largest population was served by such plants, some of which included miscellaneous processes in addition to disinfection.

Rapid sand filter plants served 40.6 percent of the total population served by all types of treatment plants.

APPROXIMATELY 74 percent of the 22,676 separate communities surveyed by the United States Public Health Service (including all incorporated communities of 100 population or more in 1940 and those unincorporated communities of 500 population or more in 1940 for which figures were available) were served by water supplies. Only in the under-1,000 population group does the percentage of communities served fall below 90. In this group, 60.5 percent of the communities listed were served by public supplies.

About 65 percent of the places of fewer than 500 persons receive untreated water. The percentage of communities receiving untreated water declines rapidly with increasing size of the community.

In the larger communities, supplies dependent on surface sources serve the highest percentage of population, and the largest populations receive treated water. The 93 places of more than 100,000 population, which comprise only 0.6 percent of the total number of communities having public supplies, serve almost 50 percent of the total population served by public water supplies.

IN ABOUT 68.9 percent of the communities, the supplies are publicly owned; in about 30.4 percent they are privately owned; and in about 0.7 percent they are publicly and privately owned.

There is no generally accepted definition of what constitutes a water system. But many authorities believe that 200 persons is the smallest group for which supply installations can be self-supporting, and enumerations of waterworks are made properly on that basis.

An extraordinary growth of suburban residential projects, many of which include a water system separate from that of the central city, occurred after 1945. On that basis, the estimate was made that there were 18,000 localities of 200 or more persons in 1955 with public water supplies.

THE COMMUNITIES in the United States that had public water supplies in 1950 may be tabulated as follows: 93, more than 100,000 population; 1,141, more than 10,000; 2,267, more than 5,000; 8,314, more than 1,000; and 8,436, under 1,000.

One is struck by the great preponderance of small towns that operated water systems. Ninety percent of all water supplies are in towns of 5,000 or less, and 50 percent serve the needs of towns of 1,000 persons or less.

The great number of water systems in small places presents a challenge to the technical advance of our water-supply operations. One cannot reasonably expect that in a town of 1,000 or less, the waterworks operator will be a technical school graduate or even one who has acquired his skills through other than an unplanned experience. Therefore some persons advocate the county control of water systems that serve fewer than a thousand persons and county guidance for those serving from 1,000 to 5,000 users.

THE AVERAGE DAILY use of water in the United States in 1900 was less than 95 gallons a person. The figure was 138 in 1950 and 143 (estimated) in 1955. For that service the average per capita cost was a little more than 2 cents a day in 1950.

The total per capita use of water in United States cities may be estimated as follows: For residential uses, 50 gallons; industrial, 50 gallons; public (fire fighting, street washing, and so on), 10 gallons; commercial and industrial, 20 gallons; loss (through leaks, breaks, et cetera), 10 gallons. The use of water in municipalities is largely nonconsumptive—not more than 10 percent of it fails to return to the watercourses below cities.

M. A. Pond, of Yale University, published in 1939 an extended study of the domestic water use in New England. He arrived at a figure of 20 gallons a person a day as the minimum amount needed to carry out properly the functions of life. He allowed 1 gallon for drinking, 6 gallons for laundry, 5 for personal cleanliness (but without tub or shower bath), and 8 for two toilet flushes. He allowed 25 gallons for a tub bath and 5 (per minute) for a shower.

THE NEED FOR WATER for sprinkling lawns is seasonal and depends on the frequency of rain and the area of lawn. O. M. Scott & Sons in 1953 reported a study of needs and costs of water in cities from the east coast to Wichita, Kans. They estimated that in that area (not including the Southeast, the Southwest, and the Pacific Coast States) 10 inches of water would be needed by a lawn for the season. The cost of 10 inches of water for 1,000 square feet watered was 0.56 dollar in Philadelphia, 2.50 dollars in New York

suburbs, and 2.63 dollars in Wichita.

The consumer demand in American cities is growing at a rate of about 1 gallon a person a day annually. Contributing to the increase are air-conditioning installations, home laundry machines, automatic dishwashers, garbage grinders, lawn sprinkling installations, and so on. Such demands may increase or flatten off as economic conditions improve or become static. All are what may be termed luxury uses of water. They probably will continue to increase.

SINCE 1946 THE SALES of some water-connected devices have gone up. Fewer than 30,000 air conditioners were sold in 1946; 1,075,000 were sold in 1953. More than 2 million washing machines were sold in 1946; 3,014,000 were sold in 1953. About 100,000 garbage disposers were sold in 1947; 353,000 were sold in 1953.

Two firms sponsored a study at Ohio State University to ascertain just how much hot water an average family of five would use for strictly household purposes. The annual total household use, not including toilets, was at the rate of 7,500 gallons a month—almost 24.6 gallons a person a day.

During the 8 months covered in the study, almost 25 percent of the water used in the home was hot. Of a total of 14,825.4 gallons of hot water, 2,744 gallons were poured through the kitchen sink; 2,562.5 gallons were used in the dishwasher; 1,908 gallons were used by the laundry machine; 464 gallons were used in the utility sink; 4,830 gallons were used in the tub and shower; and 2,316.5 gallons were used in the lavatory.

Hot showers each required 15.2 gallons of hot water. Each tub bath required 11.4 gallons of hot water in winter and 9.4 in summer.

The water cost 3.37 dollars during the period of the study; the sewer service charge was 1.57 dollars, and the gas used to heat the hot water cost 15.68 dollars.

A study of water use and family income in 15 communities in Illinois in 1947 disclosed that in low-income families the residential water use was as low as 10 gallons per capita daily; high-income families used 52 gallons per capita daily.

AMERICANS have invested more than 7,500 million dollars in the public water supply works.

In a single day the waterworks produce more than 14 billion gallons—almost 60 million tons—of safe drinking water.

During the summers of 1953 and 1954, deficient rainfall caused almost half of the United States water systems to set some sort of limitation on water use or fail to meet completely the customer's demands.

The gradual growth of demand and the deficiency in rainfall found many water systems unprepared to serve the customers satisfactorily. A significant fact was that in many instances the failure lay in the lack of storage or distribution capacity. Or, to put the situation in another light, those responsible for providing improvements in water systems have not allotted the money necessary to keep up with the customers' needs. The waterworks industry faces a tremendous backlog of needed extension to catch up with the growth of the customer's requirements.

THE USE OF WATER in the United States in 1950 and the estimated needs in 1975 are given in a report by the President's Materials Policy Commission as follows (in billions of gallons a day):

	1950	*Percentage of total*	*1975*	*Percentage of total*
Municipal/rural	17	9	25	7
Direct industrial	80	43	215	62
Irrigation	88	48	110	31
Total	185	100	350	100

The increases in needs for water in the 25 years was estimated at 50 percent for municipal supply, 170 percent for industrial uses, and 25 percent for irrigation. The growth in population for the same period was estimated at 33.1 percent. Therefore a per capita increase in city water use of more than 1.5 times the rate of population increase was cited.

The increases must be thought of in mass effect: The city of 10,000 in 1950 will be a city of 13,300 in 1975; the average daily consumption of water in that city in 1950 was 1,400,000 gallons; in 1975 it will be 2,067,000 gallons.

In other words, any city in the United States can expect by 1975 a growth in population and an increase in the rate of water use of such size that the city will have to provide 142 percent of today's supply for tomorrow's city. That is an average day.

Assuming that the peak demand in 1975 will correspond to the 1953 record, we can compute that the average city will need to provide facilities to meet a 1975 peak day reaching 235 percent of its 1952 average day.

We have no evidence that any part of the United States is growing drier, but shortages of rainfall have forced some cities to plan for more storage than they have previously provided to bridge the periods of low rainfall.

As a means of supplementing the water resources of an area, cities in the Southwest and the Far West have developed efficient sewage treatment plants to the degree that the effluents of the plants can be used for recharge or for irrigation.

There appears to be no reason why the available rainfall in the United States cannot be stored in reservoirs or in the ground or allowed to flow in regulated streams in sufficient amount to meet the needs of communities whose future may depend on their supplies of good water.

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The Increasing Use of Water by Industry

Harry E. Jordan

The industrial capacity of the United States has tripled since 1939, when the value added to goods by manufacture amounted to 24,487 million dollars. In the same period industry increased its use of water 36 percent.

Most of the water used by industry is used for cooling—a particularly dominant need in the production of steel and synthetic rubber and the manufacture of aircraft engines and explosives.

The food industries, pulp and paper mills, and meatpacking plants are among the industries that use a great deal of water in processing. A third major use of water in industry is for the generation of electric power, when part of the water is transformed into steam; but the major requirement is water for condenser cooling.

Only since 1945 or so have people thought seriously about the amount of water that industry requires. Individual factories adjusted themselves to water shortages. Large water-using industries, such as steel and paper mills, were located near streams and lakes, where the water supply appeared to be ample.

The President's Materials Policy Commission estimated a total industrial use of 80 billion gallons a day in 1950 and forecast that that amount would grow to 215 billion gallons a day in 1975. The report pointed out that industry accounted for 35 percent of the total water used in 1950 and that by 1975 industrial needs would increase to 63 percent of the national total. The differences in estimates have arisen primarily because the 247,000-odd manufacturing units in the United States in 1950, were not required to report their intake of water. Many that now make reports do so on the basis of

the rated capacity of their pumping units—a basis that is bound to develop overestimates. Reports of the industrial use of water are generally based on intake. For large industrial units alongside a lake that may refer actually to water pumped, used for cooling, discharged into the lake, and then repumped for use in another part of the same plant. The consumptive use involves only a little of the total intake.

A survey by the National Association of Manufacturers in 1950 disclosed that in factories whose intake was more than 10 million gallons a day, 54 percent of the water was used for cooling, 32 percent in processing, 9 percent for boiler feed, 6 percent for sanitation and cleaning, and 4 percent for unclassified operations. The total, which is more than 100 percent, includes the 5 percent of the intake that was reused.

In the plants using less than 10 million gallons daily, cooling took 23 percent of the pumpage; process water, 36 percent; boiler feed, 12 percent; sanitation, 26 percent; and unlisted uses, 3 percent.

Almost 40 percent of the plants recorded a reuse of water averaging 24 percent of the intake. The petroleum industry reuses 98 percent of its intake; pulp and paper, 52 percent; drug and chemicals, 35 percent; and aircraft, automobiles, iron and steel, 25 percent.

The reuse of water will expand as the Nation's needs increase.

An example of water conservation is at the plant of the Kaiser Steel Corporation in Fontana, Calif. Instead of a 65,000-gallon intake a ton, characteristic of the steel industry, Fontana requires 1,400 gallons a ton. The Kaiser mill operates its water supply in a series of seven uses with subsequent cooling—flowing the water along the path of increased temperature applicable to each use. Large mills may pump 200 or 250 million gallons daily, but Kaiser requires only 25 million gallons.

It circulates water within the plant at the rate of 144 million gallons a day. Actually, the 25 million gallons a day represents the consumptive use within the plant—largely represented by vaporization during process cooling or in cooling towers and ponds.

Sheppard Powell, an industrial engineer of Baltimore, has proposed 16 steps whereby an industry can reduce its water intake:

Install meters on all types of use;

Reduce pressure in the piping systems to the lowest practicable level;

Place thermostatic controls on cooling systems;

Use automatic valves on controls;

Check all sanitary fixtures for waste;

Keep equipment clean;

Insulate hot and cooled water service pipes;

Make surveys of leaks frequently;

Use separate pipelines for various "grades" of water;

Recirculate cooling water as many times as possible;

Reuse water wherever conditions permit;

Adjust all processes to require less water;

Treat waste condensate for reuse;

Recondition waste and wash waters;

Look for substitutes for water, such as air for aspirating or siphoning;

Appoint a water-control engineer to keep the water-saving program in operation.

The use of reclaimed water or the effluent of sewage works is practiced more and more in industry—notably steel mills, oil refineries, railroads, and metal-processing plants—as a way to get needed water. At the Sparrows Point plant of the Bethlehem Steel Co. in Baltimore, Md., fresh water, sea water, and reclaimed water are used for one or another operation. About 35 to 50 million gallons a day is fresh water, 135 to 150 million gallons is sea water, and 50 to 100 million gallons is reclaimed water from the Baltimore sewage treatment works. The steel mill treats the effluent with alum to reduce turbidity and with chlorine to prevent the growth of slimes and algae.

Amarillo, Tex., found it necessary to enlarge its sewage treatment works.

The Texas Co. needed more water for its enlarged refinery. A 30-year contract was negotiated in 1953, by which the city is to furnish the refinery reclaimed water of a quality satisfactory for refinery use. The Texas Co. agreed to make annual payments to the city in an amount sufficient to amortize the cost of facilities installed for the company's benefit. The design capacity of the sewage treatment works is 4.5 million gallons a day. The reclaimed water is to be furnished to the company at the rate of 3.75 cents for a thousand gallons. The regular city supply is sold in equivalent quantities at 13.5 cents for a thousand gallons.

The payments are to be adjusted annually on a basis of actual costs. If it becomes necessary to maintain a free (oxidizing) chlorine residual in order to eliminate ammonia from the reclaimed water, the cost to the company may rise to 6 cents for 1 thousand gallons. The municipal works in 1954 delivered an effluent that contained 14 parts per million of ammonia. Studies have indicated that 10 parts per million of chlorine is required to oxidize 1 part per million of ammonia. The new sewage-treatment works has a lagoon of 9 million gallons capacity for storing the reclaimed water. This was considered necessary to balance the rate of sewage flow and to equalize over a period of approximately 48 hours the hourly variations in the chemical characteristics of the reclaimed water.

As industrial production and urban population grow, we can expect that industry will intensify its effort to economize in the use of water and extend its use of reclaimed water.

Just as cities face the problem of eliminating waste of water from their mains and waste of water by consumers—through complete metering—so industry faces the need to conserve water by every possible method.

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Water Supplies for Homes in the Country

Harry L. Garver

Rural homes get water from wells, springs, cisterns, lakes, ponds, streams, and canals.

Water from any of those sources may be unsafe, but water that comes from surface sources needs always to be regarded with great suspicion. It is wise to get advice from State or local health departments before using water from any new source. Before one uses surface water, he should have a sanitary survey made.

Where can one find underground water? There is no sure answer to the question. Experienced well drillers and geologists have acquired a knowledge of ground water that often guides them to a suitable location for the well.

Ground water seldom flows in well-defined narrow channels, like rivers and creeks, but rather more like lakes seeping or percolating slowly through extensive layers, or strata, of sand and gravel or other water-bearing materials. If a water-bearing stratum—aquifer—lies under a layer of solid rock or tight clay, it may receive the water in some area at considerable distance from the location of the well. Frequently the supply area or catchment basin for the aquifer is at a much higher elevation than the well. Then the water, if it is confined beneath an impervious rock or clay stratum, may be under pressure just as if it were confined in a U-shaped pipe. A hole drilled in the top of the pipe at the lowest point will cause the water to rush out, its force depending on the head in the legs of the U-shaped tube. There may or may not be enough pressure to cause the water to flow over the top of the well, but if there is enough pressure to cause the water to rise above its normal upper surface it is known as artesian water.

Not all underground water flows in relatively broad sheets. Water, sometimes called the universal solvent, in time will dissolve most solids. Some rocks and some minerals dissolve very slowly, but others dissolve comparatively rapidly in water. Water flowing through or over those rocks and minerals carries some of the material in solution. A common example is the dissolving of limestone. Such water carries part of the calcium, or lime, of which the rock is composed along with it and is known as hard water. Often the dissolution of the rock takes place in such a way as to start definite channels; in time, perhaps in several thousand years, a natural cave may be formed. The Mammoth Cave of Kentucky and the Carlsbad Caverns of New Mexico are examples.

WATER MAY ENTER THE CAVERNS through crevices in the rocks. In time sinkholes are formed. Dead animals, trash, and other debris should not be dumped into sinkholes, because water that goes into them is likely to get into a cavern stream with little or no filtering, oxygen, or sunlight to purify it. It is probably accidental when a well driller hits one of these streams, but if he does the well that taps the stream is likely to be unsafe to use.

Water that comes to the well through subterranean caverns should be viewed with suspicion. It may be safe, but it is more likely to be contaminated than water that has been filtered through thousands of feet of fine-grained material. There can be no certainty that water from any new source is safe until tested by a competent technician. It may be clear and cold, but not necessarily potable—that is, safe and good to drink. Safe water should not be confused with pure water. Distilled water, an example of a pure water, is flat and tasteless. You cannot determine the potability of water by its taste, appearance, or odor.

Wells are dug, drilled, driven, or bored. Dug wells are usually shallow. All wells need to be carefully protected at the top to prevent the entrance of surface water. Water that seeps down through the upper few feet of earth may be considered as surface water. In general, water that has percolated through a vertical distance of 10 feet of compact earth is pretty well filtered.

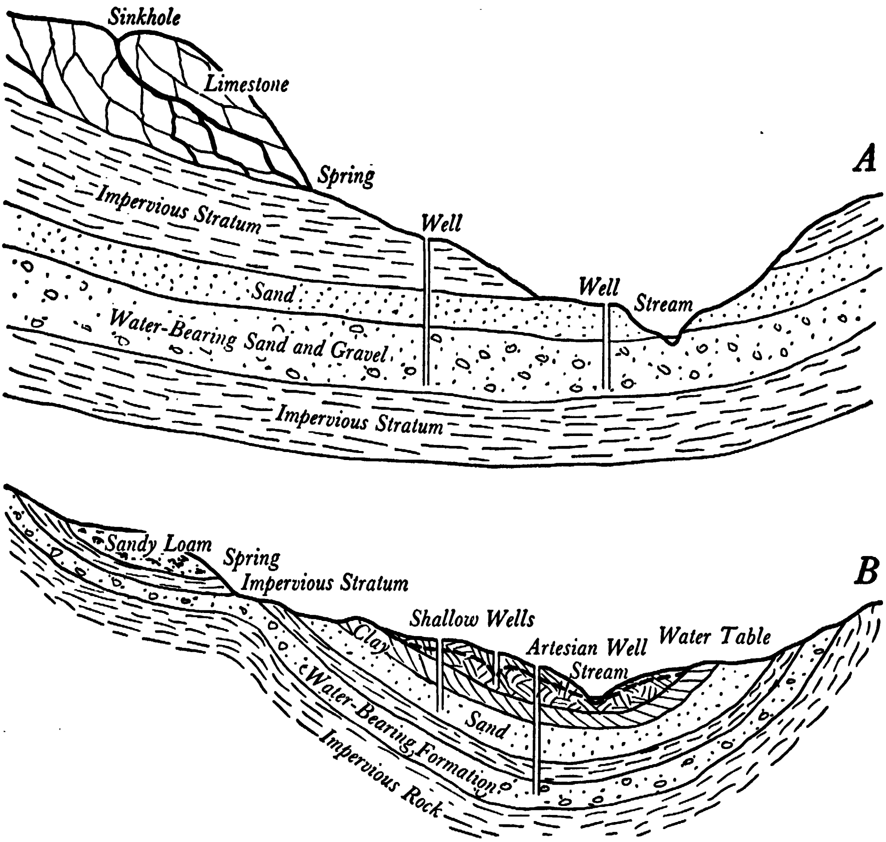
Drilled wells are usually deep and frequently extend through solid rock or strata of hard material practically impervious to water. Drilled wells are usually cased to the impervious strata and are more likely to yield safe water than shallow wells. Bored wells are usually in the same class as dug wells. Driven wells, like dug wells, usually are shallow, too.

Almost any source of water may become contaminated through flooding or other accidents. Carelessness during repairs may cause contamination of the water. It is recommended that all newly developed water supplies be disinfected. It is a good idea to disinfect the water system after repairs or extensions, especially extensive ones, have been made. That can be done by chlorinating the water. Your local health officer can tell you how much chlorine to use.

WATER MAY BE DISINFECTED by adding chlorine in amounts sufficient to oxidize all the organic matter. The chlorine remaining after that is done is called residual A small amount of residual chlorine is harmless and is an indication that the water has been rendered safe as far as bacteria are concerned. Up to 0.5 part per million residual of free chlorine is generally considered satisfactory for domestic water. Equipment for testing for residual chlorine is available from manufacturers of chemicals and laboratory equipment. Water may be rendered safe by boiling for 5 minutes.

Two drops of 7-percent tincture of iodine stirred into a quart of clear water and allowed to stand for half an hour will usually make it safe to drink.

Always when any contamination is known or suspected it is wise to consult the public health officer about it.



Earth strata, showing water-bearing formations. Horizontal distances are foreshortened and slopes exaggerated. A, Sinkhole shown as a likely source of contamination of water moving through rock seams; B, earth strata, showing possible sources of good water.

The yield of the well is not necessarily proportional to either the depth or size. The well should extend into the water-bearing formation to receive water. The depth will depend on the nature of the formation. Coarse sand and gravel will allow water to move through readily. Clay and rock resist the flow of water; hence, the well must penetrate them to obtain an equal flow. Two wells placed close together will not produce twice as much as one well. The influence of one well on another may be felt for a considerable distance. The diameter of the well is not important as far as yield is concerned. It should be large enough to accommodate the type of pump that is to be used. A well that is used for storage must have a large diameter.

Springs occur in places where ground water reaches the surface. Water from springs may or may not be safe, depending on the source of water supplying them, the material through which the water flows, and how the water is treated at the point of emergence.

The taste in waters is due to dissolved mineral salts and other ingredients. If the material carried by the water is harmful, the water is said to be contaminated.

Water that contains calcium and magnesium salts is called hard. The

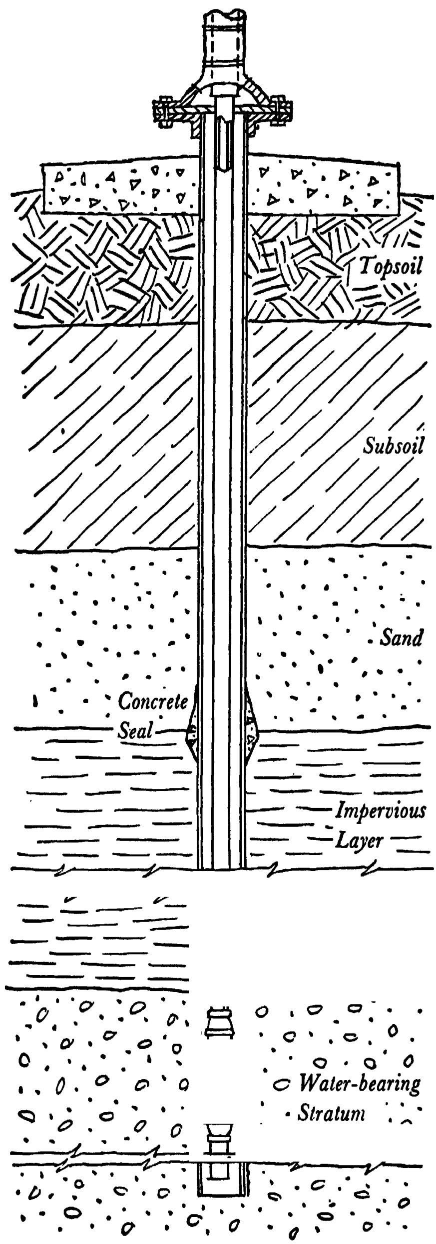
degree of hardness can be measured by the amount of a standard soap solution required to produce a permanent lather in a measured volume of water when shaken together. The result is expressed in p. p. m. (parts per million) or in grains per U. S. gallon. One grain per gallon is equal to approximately 17.1 p. p. m.

Total hardness of natural water may be bicarbonates or sulphates, chlorides, or nitrates of calcium, magnesium, iron, or other minerals. Carbonate hardness often is called temporary and can be removed by boiling. They leave an insoluble scale on the walls of the boiler, water heater, or teakettle, and leave a cloudy surface on glassware.

The noncarbonate hardness is often called permanent hardness. Water having a hardness of 15 to 50 p. p. m. is thought of as soft water; 50 to 100 p. p. m. as medium hard; 100 to 200 p. p. m. as hard water. Hard water is satisfactory for irrigation. Water under 150 p. p. m. is preferable for domestic purposes. Very soft water, while good for use in laundering, dishwashing, and bathing, may be corrosive to water pipes.

Two methods of softening water in common use are the lime-soda process and the zeolite, or cation-exchange, process. The lime-soda process is used mostly in treating large volumes of water for cities and factories. The cation-exchange process is used most commonly for softening individual family supplies. The process is a base exchange, in which as water passes through the softener calcium and magnesium are exchanged for sodium.

The zeolite must be reactivated after it has picked up all of the calcium and magnesium it can. Reactivation is done by passing a solution of sodium chloride (rock salt) through the softener and backwashing with clean water. Zeolites may be natural or synthetic green sand. The synthetic zeolites usually are capable of removing 2 to 2.5 times as many grains of hardness as the natural zeolite. Some idea of the amount of



Well drilled through several soil and rock layers, or strata, into water-bearing sand and gravel. Seal is shown at top of impervious layer; also concrete platform at top of well and method of attaching pump to casing.

Several drawings of other types and uses of pumps are printed in the appendix at the end of this volume.

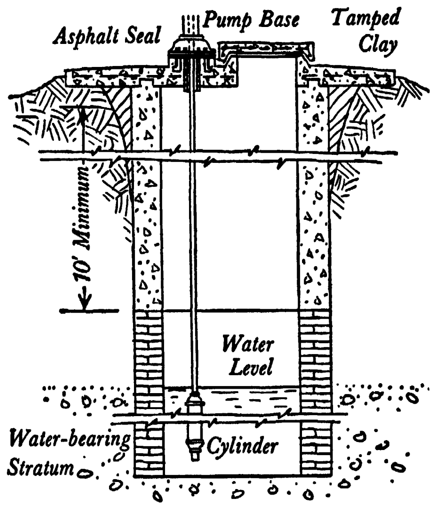
water that may be softened between regenerations may be had by noting that a cubic foot of synthetic zeolite will remove 5 thousand to 8 thousand grains of calcium.

It is not always desirable that water be completely free from minerals that make it hard, because very soft water is likely to be corrosive, especially if the pH value is very low. Then it may be advisable to bypass the softener with a little raw water to reduce corrosiveness. Copper or other nonferrous materials may be used following the softener. It is sometimes good economy to soften only the water that is used for laundering, dishwashing, and bathing.

Highly alkaline water usually will leave an incrustation on well screens, pipes, and boilers. Acid water will be corrosive. An analysis will show the pH value of water. A pH value of 7 indicates neutral water. Values above pH 7 indicate alkaline water; values below pH 7 indicate an acid condition. The chief cause of acidity or low pH is carbon dioxide (CO_2), which is soluble in water and forms carbonic acid. Good water should be nearly neutral—neither acid nor alkaline.

IRON is one of the most troublesome elements carried by water. Iron is readily dissolved by acid water and is carried as a bicarbonate. Occasionally it occurs as a sulfate and is very corrosive. Perhaps its chief offense is that it is the cause of red water, which in turn precipitates onto porcelain plumbing fixtures and onto clothing during laundering.

Iron carried in water may be removed by getting rid of the acid condition and filtering. Acid may be removed by aeration. Aeration may be very simple: The water can be pumped through a sprinkler system or dropped through a cooling tower that has numerous baffles. The water should be broken into small droplets so that the maximum surface is presented to the air. Passing the water over crushed limestone will remove much of the carbon dioxide, which is responsible for



Dug well properly constructed, with sides sealed down at least 10 feet from the original ground level.

holding the iron in suspension. The iron in the water will oxidize after the acid condition is corrected. Passing the water through a fine sand filter bed will remove the iron oxide. The filter bed must be installed in such a way as to permit a reverse of flow for backwashing and also to permit replacement of sand when necessary. Iron as normally found in underground water is not ordinarily a health hazard.

Special zeolite water treaters are available for removing iron. The treaters operate on the same principle as softeners but are reactivated by passing a solution of sodium permanganate through the zeolite.

Sometimes treatment with chlorine removes iron.

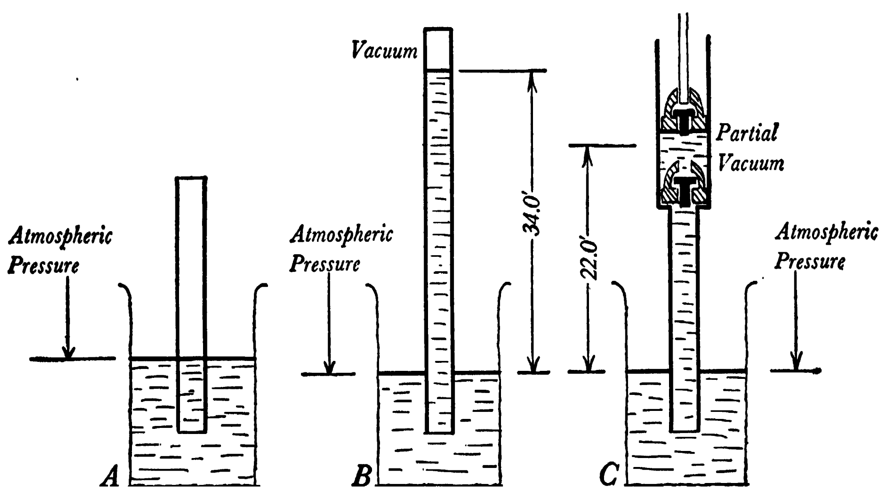
FORTUNATE is the family that can have running water in the home from a gravity system. Most homes having individual water systems must use a pump. Domestic pumps are designed for either deep or shallow wells. They may be any one or a combination of types—reciprocating, rotary, centrifugal, and turbine. All four types are suitable for power drive, but only the reciprocating and rotary types are suit-

able for hand operation. Other types are chain or bucket, air lift, and others, but only the four basic types are now common.

Ejector pumps consist essentially of a centrifugal pump, which is located at the top of the well, and an ejector located near the water surface. The ejector depends on pressure to furnish a velocity head through the nozzle. When the chamber in which the nozzle is located is properly shaped, a vacuum is created, which is filled with water from the well. This water, together with water coming through the nozzle, rises to (or nearly to) the centrifugal pump. Most of the water goes to the pressure tank, but some of it must go back to the ejector to keep it going.

The suction lift must be treated as a part of the total head. The pump creates or attempts to create a vacuum. The pressure of the atmosphere on the surface of the water outside the pump forces the water up into the pump to fill the void. At sea level the normal atmospheric pressure will theoretically force water up into the pump approximately 34 feet. The practical suction lift, however, is only about 22 feet at sea level. To determine whether shallow or deep-well pump is needed, the value of 22 feet should be used. If the surface of the water in the well exceeds 22 feet below the pump, a deep-well type of pump should be used. As atmospheric pressure decreases with increasing elevation, deep-well pumps are required to take water from wells where the surface is less than 22 feet below the pump if the well is located at high altitude. A practical rule is to deduct 1 foot of practical suction lift for each 1,000 feet the well is above sea level. Suction lift is the distance that the pump (cylinder if reciprocating; housing and runner if centrifugal) is above the water surface in the well. The low-water mark in the well should be used in determining suction lift. If the pump head must exceed 22 feet above the water surface, a deep-well pump must be used.

EACH PUMP has advantages when used for the type of pumping for which it is designed. The reciprocating pumps are positive displacement; that is, the space behind the piston or valve is filled with water during the upward stroke and held there by means of a



Suction lift caused by atmospheric pressure. A, No lift or rise inside tube when pressure inside and outside are equal; B, suction lift, with complete vacuum inside tube (theoretical); C, suction lift of pump with partial vacuum inside tube.

check valve during the return of the piston or plunger if the piston is equipped with a valve. If the piston is solid, the water will be forced up or out through a second check valve, where it is held until the next stroke forces it on. Both valves open in the same direction. If the cylinder space left by the movement of the piston will hold a pint of water, a pint will be delivered at each stroke of the piston. In a double-acting pump, 2 sets of valves and both ends of the cylinder are used, and approximately 2 pints will be delivered for each full revolution of the crank. The time required to complete a revolution of the crank is not critical. That is why the reciprocating pump works satisfactorily with hand or wind power, which often is variable in speed.

THIS CLASSIFICATION includes a fairly large number of pumps such as pitcher pumps, hand-operated force pumps, power-operated deep- and shallow-well reciprocating pumps, and diaphragm pumps. The positive-displacement pump will stall or something will break if it is allowed to operate when the system is full and closed.

The centrifugal and turbine pumps are not positive displacement. They are designed for specific speeds, especially centrifugal pumps, and are rather critical to speed changes. They will operate with the discharge valves partly closed. They will heat the water if they are completely closed and may cause damage.

Centrifugal pumps are especially adaptable if there is continuous operation and low-suction lift and large volumes of water are to be handled. Reciprocating pumps are entirely suitable if small volumes of water are pumped, operation is intermittent, and speed is variable.

SHALLOW-WELL PUMPS need not be set directly over the well or cistern, but the pipes from the water to the pump should rise vertically or slope upward toward the pump. Deep-well pump heads of the reciprocating type must be set over the well, because they require a straight rod to operate the plunger. Ejector, or jet-type pumps, may be set at some distance from the well for either deep or shallow wells. The suction pipe should be vertical or slope upward all the way to the pump head.

Submersible pumps, widely distributed, consist of a multistage centrifugal pump and motor combination that is lowered into the well to below the draw-down level of the water.

PUMP PITS over wells are not recommended because of difficulties from poor drainage. They are a source of contamination unless they are effectively drained. The dampness may harm the motor and make the place hazardous when the electric circuits are alive. The pump and storage or pressure tank and all the pipe and fittings, however, must be placed in frostproof enclosures in places where freezing is likely to occur. That may require an insulated pump house. A well insulated pump house may be heated sufficiently to prevent freezing by a lighted 100- or 200-watt lamp hung near the pump.

WATER MAY BE PIPED around the farmstead in a main line from which a lateral extends to each building. Pipe of any kind must be laid below the probable frost depth. Somewhat greater care must be exercised in backfilling the trench with plastic or copper tubing than with iron pipe. Plastic pipes are being used to a limited extent for the cold-water distribution system in buildings. It has not been recommended for hot water.

Plumbing in farm homes need differ little from plumbing in urban homes. A few basic principles must be observed in all plumbing and water supply systems:

All fixtures must be supplied with enough water at adequate pressure to make them operate properly.

Devices for heating water must be

installed and equipped so there is no danger of explosion.

Cross-connections with other water supplies must be avoided, particularly if there is any likelihood of contamination.

Connections to fixtures must be such as to prevent back siphonage.

Piping must be sized to keep pressure drop to an economical minimum.

THE SIZE OF PIPES to the various buildings will be determined by their length and the amount of water required. Usually the pipes are three-fourths inch or 1 inch. Distribution inside the farm buildings is usually simple, and the runs are short. The recommended size of pipes extending from the distribution system to individual fixtures, known as fixture supply pipes, is one-half inch for all fixtures, except the lavatory and water closet, which may be three-eighths inch.

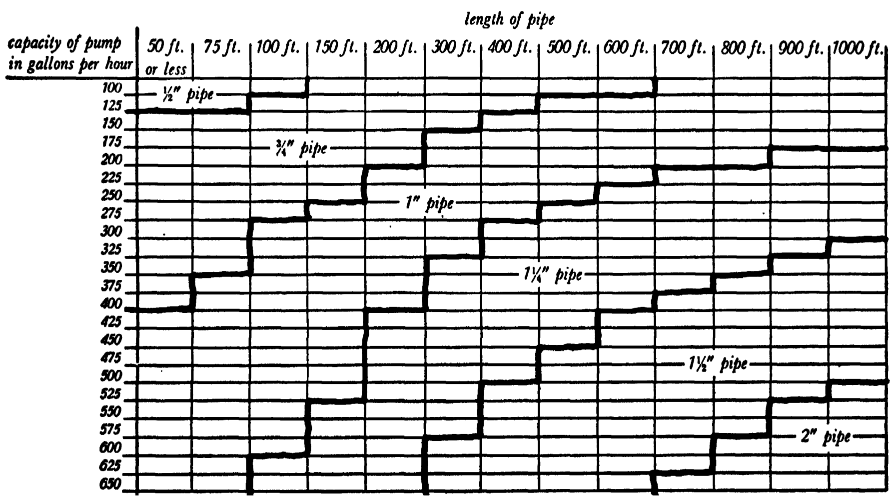
Suppose your pump has a capacity of 350 gallons an hour, and there are 200 feet of pipe from the water-storage tank to the barn. About halfway down the column in the accompanying chart, headed "capacity of pump in gallons per hour," you will find a figure 350. Read across the page from 350 until you come to the column directly under 200 feet. You will notice that you are now in a part of the chart labeled 1-inch pipe. This means that 1-inch piping would be the correct size.

Of particular importance in planning any water supply is to have an adequate amount. The following amounts, in gallons a day, are suggested as values to use in determining needs: For each member of the family, 50 gallons a day; each milking cow, 40; each beef animal, 12; each hog, 4; each sheep, 2; each 100 chickens, 10; each 100 turkeys, 5.

The pump should be of a size that it will furnish the daily needs in 2 or 3 hours of pumping a day if the well will yield water at that rate. If not, the pump must be sized to the rate at which the well will furnish water.

PROVISIONS SHOULD USUALLY be made for storing a certain amount of water. There are three ways to do this: The dug or bored well may be large enough to provide storage capacity, an elevated tank can be provided, or a

Pipe Size Selection Chart



pneumatic tank can be placed in the system.

When the well is used for storage, the pump must operate every time water is drawn. The elevated tank frequently requires considerable pipe or rather expensive supports. This type of storage lends itself readily to fire protection. The pneumatic pressure tank is somewhat limited in capacity but is easily installed in the water system.

Some idea of the size of pressure tank needed can be obtained from the following details. For a given temperature, the pressure of air is inversely proportional to the space it is forced to occupy. Thus, if a tank filled with air at atmospheric pressure (14.7 pounds at sea level) has water pumped into it until it is about six-tenths full, the gage will read about 22 pounds. When the gage reads 41 pounds, the tank will be three-fourths full. Thus, if the pressure control is adjusted to cause the pump to start at 20 pounds and stop at 40 pounds, only about 15 percent of the total capacity of the tank can be drawn without causing the pump to start. If the tank is filled with an initial pressure, somewhat more water can be drawn between the same limits of pressure.

Individual water systems seldom handle enough water to be of much value in controlling a serious fire, but any of them may be useful in putting out a fire in its early stages. If fire control is contemplated, it is well to have one or more protected reservoirs or cisterns strategically located about the farmstead. Fire-fighting pumpers may handle as much as 500 gallons a minute. At that rate the reservoir would have to hold 7,500 gallons to keep the pump going for 15 minutes. Fog nozzles will require much less water. The best answer to the question about size and location of water storage for fire-fighting purposes can be obtained through consultation with the chief of the local fire department.

A reservoir to hold 7,500 gallons should be 10 feet by 10 feet by 11 or 12 feet deep if it is square; if it is round, it should be 13 feet in diameter and 13 feet deep. The reservoir should be covered as a safety measure and to prevent it from becoming a breeding place for mosquitoes. A good light-tight cover will prevent the growth of algae.

HARRY L. GARVER *joined the Department of Agriculture in 1938 and has held several positions related to agricultural engineering.*

Safe Sewage Disposal for Rural Homes

Harry L. Garver

The sewage disposal system of a house consists of at least two parts—the plumbing inside and the drainage system outside the house.

For the average family the selection of plumbing fixtures is somewhat a matter of personal preference. The fixtures may be of colors that blend with other colors in a room. The space they will occupy will determine to some extent their size and shape. They must be properly supported. The empty bathtub weighs 300 to 500 pounds. Twenty gallons of water will add another 175 pounds. When a heavy man gets into the tub, a fairly concentrated load is placed on the floor joists. Consideration should be given to this weight in designing the house. All fixtures should be set as nearly level as possible. Faucet spouts should be set so that the openings are about 1.5 inches above the rim over which contents spill when the fixture overflows.

All plumbing fixtures must be equipped with traps, which may be part of the fixture or placed in the fixture drain. Their purpose is to prevent the free flow of gases from the sewer or septic tank. Water flowing through a pipe tends to pull air through with it. That phenomenon would pull

the water out of the trap if there were no other path for the air to enter. Then, too, if the gas pressure in the sewer system became high enough it would bubble through the water in the trap. To keep the air or gases from breaking the trap seal, a vent pipe must open into the drain a short distance from the trap on the drain side. One vent may serve the traps of a group of fixtures if they are close to the soil vent or stack—30 inches if the fixture drain is 1.25 inches in diameter; 42 inches if the drain is 1.5 inches; 5 feet for a 2-inch drain; and 10 feet for a 4-inch drain.

The soil pipe is usually continued up through the roof of the building. The part above the highest horizontal drain is known as the stack-vent. Fixtures located too far from the soil pipe to be vented properly by it may have their individual vents, which are connected to the stack-vent. Such vent connections are called loop vents.

Usually cast iron soil pipe is specified for use under a concrete floor and through the foundation wall. Outside the foundation wall, any material permitted by the local code or authority (where such authority exists) may be used. Often clay tile is used. Some use bitumenized fiber and other materials.

If your community has a public sanitary sewer into which sewage from your buildings will drain, your building drain pipe should empty into it. Most rural and farm homes are not so fortunate. In that event, the use of a septic tank is recommended as a means of sewage disposal. The drain pipe to the septic tank should slope one-fourth inch a foot. Pipe 4 inches in diameter ordinarily is recommended. The septic tank may be of steel, masonry, or monolithic concrete. Regardless of its material, it should be leakproof.

The size of a septic tank should be based upon the number of persons likely to use it. Since families change and property is bought and sold, it is difficult to design for the number of persons, so the size is usually based on the number of bedrooms. It is recommended the tank have a liquid capacity of at least 500 gallons.

Liquid capacity is measured below the bottom of the outlet pipe, which is usually 12 to 15 inches below the top of the tank. The inside dimensions usually recommended are given in the table. Disposers of food wastes increase both the liquid and solids going into the tank. The amount depends largely on the habits of the family. To insure sufficient sludge capacity, it is recommended that the capacity of the tank be increased 50 percent over that shown in the table below. If the tank is in place when the grinder is installed, it will be necessary to inspect and perhaps clean the tank oftener.

Septic tanks need not be rectangular if they are designed so that incoming sewage does not stir the contents of the tank very much. Tests seem to indicate somewhat greater efficiency with tanks having less depth of liquid and greater surface area. The matter of space and cost are factors that determine the dimensions of the tanks.

Ordinarily there is no need to add yeast, enzymes, or other starters to new or old tanks. Raw sewage contains the necessary bacteria for digestion of solids. If for any reason it is believed

Number of bedrooms	*Maximum number of persons served*	*Liquid capacity of tank in gallons*	*Recommended Dimensions* — *Width* *Ft.*	*Width* *In.*	*Length* *Ft.*	*Length* *In.*	*Liquid depth* *Ft.*	*Liquid depth* *In.*	*Total depth* *Ft.*	*Total depth* *In.*
2 or fewer...	4	500	3	0	6	0	4	0	5	0
3..........	6	600	3	0	7	0	4	0	5	0
4..........	8	750	3	6	7	6	4	0	5	0
5..........	10	900	3	6	8	6	4	6	5	6
6..........	12	1,100	4	0	8	6	4	6	5	6
7..........	14	1,300	4	0	10	0	4	6	5	6
8..........	16	1,500	4	6	10	0	4	6	5	6

that a new tank is not functioning as it should, a few gallons of sludge from a tank that is known to be operating satisfactorily may help.

The septic tank should be inspected periodically and cleaned as needed. A number of proprietary products have been placed on the market that are supposed to dissolve solids in septic tanks, but none of those tested by the Public Health Service takes the place of an occasional pumping out. Some of them may be detrimental to the proper operation of the tank and disposal field.

When a person inspects a septic tank, he should not use matches or an open flame, because the gases produced by decomposing sewage may explode.

The tank should be cleaned when the scum and sludge occupy one-third to one-half of the liquid capacity of the tank. Annual inspection may be the means of avoiding serious trouble and expense with the sewage system. The amount of accumulation can be determined thus: Attach a strip of towel to a stick and push it through the inspection hole to the bottom of the tank. Rotate it once or twice and let it stand a few minutes. Sufficient sludge will adhere to the rag to give a reasonably good idea of the amount of accumulation.

Synthetic detergents do not seem to interfere with the operation of a septic tank if they are used in ordinary amounts, if the tank is as large as recommended in the table, and if it has the proper inlet tee, or baffle, so that the contents of the tank are disturbed as little as possible.

A moderate use of drain solvents, mild cleaning agents, and disinfectant solutions will not adversely affect the operation of the tank after it has been in operation long enough to have accumulated a little sludge.

Septic tanks do not destroy bacteria. Care must be taken in disposing of the sludge, scum, and the effluent from the tank. Material cleaned from the tank should be taken away from the farmstead and buried where it will not contaminate any water supply.

Since the effluent of the septic tank contains bacteria, some of which may be dangerous, a safe means of disposal must be used. The best way of doing this should be one that insures killing of the bacteria by oxidation or by action of other organisms.

The accepted way of disposing of the effluent from the septic tank is to run it through farm drain tiles laid in the top soil below the probable depth of any cultivating implement or tool, say 18 to 30 inches. Trenches should be dug 18 to 36 inches wide with a slope of 2 to 4 inches to 100 feet.

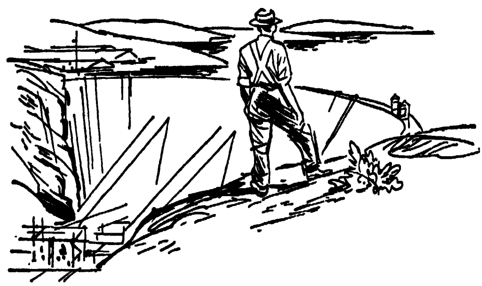
The bottom of the trench should be covered with a layer of coarse, clean gravel or broken stone to a depth of about 6 inches. Four-inch farm drain tile should be laid on top of the gravel, the sections butted tightly together. The top half of the joints should be covered with a strip of heavy asphalt paper and enough gravel added to cover the tile to a depth of about two inches. A layer of straw or a layer of untreated paper and backfill should be tramped in.

The sewer line from the septic tank to the disposal field may be glazed bell-and-spigot type of tile or terra cotta. The tile should be laid with a slope of one-eighth to one-fourth inch to the foot and should empty into a distribution box. It is practically impossible to distribute the load equally in two or more laterals by means of wyes. The size of the distribution box will depend on the number of laterals. Of special importance is the height of outlets. All laterals should start at the distribution box and all must be at the same height.

If the soil conditions or terrain are such that a disposal field is impractical, it may be convenient or necessary to resort to a seepage pit. Seepage pits must extend into porous material but they must not drain into any earth strata from which domestic or stock water is taken.

Harry L. Garver *is an agricultural engineer in the Farm Structures Section, Agricultural Engineering Research Branch, Agricultural Research Service.*

A Look to the Future



Regulation and Economic Expansion

C. E. Busby

Water is particularly subject to regulation because it is essential to human existence, because it is a changing resource that may bring good or evil to many people according to its use and management, and because some of it is subject to established public and private rights of use.

The more valuable water becomes, the more conflicts of interest arise over its use and management. The conflicts may lead to insecurity of investments and impeded or unbalanced economic growth if basic law is not provided to assure protection of rights and a fair apportionment of the supplies to satisfy the rights.

Water is a common denominator of human activity. To protect the interests of present and potential users of water, State Governments have to provide guides to encourage a fair division of the supply, the reduction of waste and damage, and the conservation of water.

All users of water depend in one way or another on the same sources of supply. Some users need surface or underground storage to help balance supply and demand—for hours, days, months, years. The supply in one area may be needed to balance the demand in another area.

But water is of special concern to the respective States, as well as to private users. When the people in each original State gained their independence, they became themselves sovereign, acquiring all the rights and the responsibilities formerly held by the King and Parliament of England. Thus many governmental powers over water reside in the States, even though the Fe 'eral Constitution granted regulatory powers to the United States over interstate commerce carried on water.

It is obvious, then, that cooperation and good government are essential aspects of local development and use of water.

Although all States and Territories have adopted legislation for soil conservation, only the 17 Western States in 1955 had adopted comprehensive legislation for conserving the defined surface streams. Fourteen States, most of them in the West, had reasonably effective legislation for ground waters.

Eight Eastern States had adopted preliminary conservation legislation for use of surface streams. Nine of the Eastern States had legislation for ground-water control, which is partly effective. A number of States, most of them in the South, had no really adequate legislation for the conservation of water, save that afforded by soil conservation legislation as it affects diffused surface waters arising from precipitation.

Our present systems of State water law developed from two major sources.

The first is the common law, which is largely judge-made. The other is statutory law, the product of legislative assemblies. Overlapping arises because some statutory principles have been incorporated into the common law, and vice versa.

The common law evolved slowly to meet the narrow issues presented to the courts in the light of past conditions. But often the thinking behind some of the common law was limited by rules of precedent, without suitable consideration of the principles of the physical sciences and future needs of the people. Thus some of the common law rules are stopgaps, rather than guides for the future. Some have become relatively inflexible and ill-adapted to conditions of rapid economic change.

In contrast, the statutory water rules made by legislative bodies evolved much more rapidly than those of the common law, upon the advice of specialists and laymen and with due regard to many issues then arising or foreseen. They incorporate basic principles from other technical fields. They are more readily changed in the light of changing conditions. But they are not perfect. Some do not provide scientific standards of beneficial use. Others are less flexible than they ought to be to meet the requirements of efficient distribution within major drainage areas. Many do not provide for reservation of supplies to meet shifting social and economic needs.

Courts and some legislatures failed in the past to provide flexible quantitative guides for future and present uses to help meet the shortages as they arise. Progress has been made in recent years in some States, and interest in better water law has grown among organizations and agencies over the Nation, especially those that serve farmers. Farmers are the ones who need the legislation most but understand their needs the least.

Our present systems of State water law are here classified according to the physical occurrence of water—water in the air, water on the ground, and water in the ground. For each, property rights may be involved and also organizations established under law for the administration of State or local programs of water development and use. The property rights may concern personal or real property, depending on whether the water is taken into possession, as in a pond or bathtub. Water in relation to the land is considered real property until it is taken into possession.

The only State laws pertaining to water in the air in 1955 were those established to regulate artificial rainmaking. Each is mainly of a licensing nature to control the activities of cloud-seeding operators. Such legislation may spread from the few States where such laws were in effect. Someday a real problem may arise from the standpoint of property rights if it can be shown that one party has taken water in the air that ordinarily and naturally would have fallen on the land of another. Such rights had not been spelled out in 1955 by any United States court, but some people believed that landowners do have property rights to water in the air. It might not be easy to determine whether one landowner or a group of landowners have the right to take from the clouds water that is needed by adjacent lands or would otherwise fall on them. In any event, farmers and State legislators need to be alert to protect their rights.

Rights to water on the ground pertain to waters of defined natural streams and lakes (the natural watercourses) and diffused waters, which usually arise from precipitation and snowmelt but have not found their way into natural watercourses. The main source of supply for live streams and lakes is ground water or springs. But a part of the supply, notably for intermittent watercourses, may come from diffused surface water runoff, especially in seasons of melting snow and in places where storms of high intensity or long duration prevail. Diffused sur-

face waters make little contribution to the supply of natural watercourses in some localities. Thus full, beneficial use should be encouraged whenever it is practical to do so.

OUR COMMON LAW tells us little as to the nature and extent of the land users' rights to use diffused surface waters. The law, such as it is, varies from State to State without a clearly defined regional pattern and deals with the right to control the movement of diffused waters or to drain lands where they have collected naturally.

One old rule is that the user may treat the waters as a common enemy and fend them off as he pleases, even though he may thereby injure the lands of his neighbor above. Another old rule holds that the upper land user has a right to have his diffused waters pass down to and over the next adjacent property without undue interruption. In other words, under the second rule, the lower user may not fend off the waters so as to injure upper lands. Under either rule, the land user may not unduly collect, concentrate, and discharge diffused waters upon his neighbor in unnatural quantities or velocity so as to cause real damage. Perhaps the latter exception to the general rules is the more practical.

But we know that farmers work all the time with diffused waters in one way or another. Our courts have made numerous statements about rights of landowners to use diffused waters by reason of the title they hold to their lands. In nearly every case the issues before the courts have not concerned rights of use but rather damage caused by artificial changes in the movement of waters. And our legislative bodies have not provided us with guides.

Therefore it would seem that two broad legislative rules might be established to guide users as they increase beneficial use of diffused waters:

1. Natural capture: Where natural depressions occur on farms and are not big enough to be recognized as well defined natural lakes, it would seem that the landowner by reason of his title ought to have absolute ownership of the water collected in the natural pond. If two or more landowners together have one such pond on their lands, they ought to own the supply in common, with some provision for apportionment of amounts on the basis of acreage on which the pond rests or some other fair basis. Failure to provide some such rule of apportionment can lead to competitive deepening of the pond by each owner, who may seek to take all the supply he can reduce to possession within his own land area.

2. Artificial capture: Where natural depressions, as indicated above, do not exist on farms, it would seem that the landowner by reason of his title ought to have absolute ownership of the diffused surface waters which he may be able to collect and capture on his own land by applying adapted conservation measures, as long as the use of the water is necessary to the wise use and management of his own land; the waters so collected are not allowed to be concentrated and later discharged upon the lands of another to his injury; and the use on one or several farms will not adversely affect the rights of the users of water on streams or lakes below. If two or more landowners collect and capture diffused waters by these means, they ought to own the supply in common if it is stored in an artificial pond or other community collection system. Here again some criteria for quantitative apportionment would be desirable.

These types of legislative guides have received consideration by some legislative committees in the Eastern States.

OUR COMMON LAW of defined natural watercourses, otherwise known as riparian law, tells us something about the nature and extent of rights to the use of water. It was in effect in all Eastern States and in some of the 17 Western States in 1955. Even so, the farmer is left with many unanswered ques-

tions. Often, in the final analysis, he must go to court to have a jury determine his use as it may affect the use of others whose land is on the stream or lake below or adjacent to his. Here rights of use arise out of the ownership of lands. But the landowner does not own the water in the stream—nor does anyone else. Many farmers do not understand that point.

Access to the water is the key point. The lands must somehow touch the stream or lake. It may be the bank or middle thread of a nonnavigable watercourse, or the high watermark of a defined navigable watercourse. Title to land on navigable waters has been extended in some States by statute to the low watermark and in some respects to the line of navigability.

Those who do not own lands touching the water body, as here outlined, do not have rights to use those defined waters. Among them may be owners of lands that at one time comprised parts of original land patents granted by a State, carried riparian rights for a time, and were later sold or otherwise disposed of without expressly reserving water-use rights in the deeds or other lawful conveyances. They may include lands that were later repurchased by the original owner or his successor. Once the land is completely severed by lawful means from access to the body of water, it may never again under the common law recover water rights in the natural watercourse. That is a basic point that makes the riparian system ever contracting, never expanding.

Streams may not be diverted from one watershed to another under the common law. That further narrows down the opportunity for land users to obtain a suitable water supply to meet their expanding needs, particularly for irrigation.

Although a certain landowner may exhaust the stream to satisfy his natural domestic needs, which include water for the household, family farm animals, poultry, and other livestock, and the family garden or lawn, other users are limited to a so-called reasonable share for artificial needs, such as for irrigation. This share often is difficult to ascertain and in a strict sense cannot be exercised until all domestic uses are satisfied. In general words, it is that portion or use of the common water supply that is reasonable in relation to the like rights of use of all other riparian landowners lying below on the same stream. That limitation is not very burdensome if the common supply is plentiful. But if the supply is small, the share may be less than will support efficient operations. This leads to insecurity of investment as expansion in consumptive use increases.

What is a reasonable use of the common supply of one in relation to that of the others?

Our courts say that that depends on all the circumstances surrounding the case in the particular locality where the competition over water arises, such as the size of the stream, the nature of the uses, and the types of storage, diversion, and use facilities. Because the question of reasonable use is one of fact, which a jury must decide, the water user must go to court to get the answer. That would be all right if litigation were not a costly business, especially when several competing users are involved. It would be all right also if juries did not vary from one locality or time to another as to what is a reasonable use.

Many farmers outside the main irrigated areas of the West are rapidly increasing their acreage of irrigated lands in order to protect themselves and their enterprises against drought and to meet competition.

But many such farmers get their water from streams that run low or dry in the season of great demand. Thus storage of water in the soil and in reservoirs during seasons of high rainfall and runoff is imperative if demands are to be met in the dry seasons.

Is storage for any considerable period a reasonable use of the stream under the riparian system? The courts of some of our so-called humid States

have not given decisions as to irrigators who store water and as to other users who store water, particularly nonconsumptive users. Seasonal storage has not been generally considered a reasonable riparian use in these States.

As between nonconsumptive users of water for power purposes, courts in the East have ruled that the upper user may store water for the preceding night or day in order to have enough head to produce power for the next day or night. That has been held to be a reasonable use, even though it deprives the lower user of the common supply for several hours and causes a shutdown of his operations. We cannot say for sure what the courts would hold to be a reasonable use in the more humid States in the face of long-established power uses coming in conflict with newly established irrigation uses supported by needed seasonal storage.

Another aspect of reasonable use under the common law is the type of use itself. Use by a municipality on lands that do not touch the stream is held to be unreasonable, even though the municipality may own riparian lands at the point where the water is removed from the stream or lake. Furthermore, municipal uses are generally not considered riparian uses. Many municipalities have been faced with the same types of water-shortage problems as farmers, especially on small tributary streams. Often their economies are interwoven with those of farmers. Their needs must be considered, too.

ANOTHER LIMITATION of the riparian system, one with far-reaching implications, arises out of the main concept that each piece of riparian land is entitled to have the full flow of the stream come by substantially undiminished in quantity and unimpaired in quality, except that the riparian user may exhaust the entire flow if necessary to satisfy his domestic needs. This concept is called the natural flow theory. When strictly upheld, it tends to give the lower users on the stream a measure of monopoly of the streamflow.

Domestic use of water takes a relatively small part of the total streamflow in most instances. But artificial uses, such as irrigation, take large amounts of water. When artificial uses are important and shortages may be anticipated, a quantitative guide for the division of the available water supplies among those in need is essential under a broad conservation policy that affords opportunity for all to increase their use of water without violating established rights of use. The common law riparian system provides no substantial quantitative guide to apportionment of a water supply.

Farmers must recognize some other basic weaknesses in the common law of riparian rights if they are to meet changing needs. The riparian landowner is not held to any measure of beneficial use and conservation of the water supply. His right does not arise by reason of use. And nonuse alone will not result in a loss of water rights. His rights arise by reason of ownership of land—nothing more. He may waste his water, watch it flow on to the sea, and make no contribution to improved rural living and community life—and still hold his water right as long as he holds his land. That is the common law outside the 17 Western States.

Is this consistent with the basic land policy of every State to conserve, protect, and wisely use every acre of land suitable to agricultural purposes? Is it wise to have a conservation policy for land and a policy of waste for streams?

The riparian system has several important weaknesses or drawbacks from the standpoint of the public interest of all prospective water users and investors. It is a decreasing or shrinking system as far as opportunity to use water is concerned. It contributes in the long run to monopoly and nonuse. It does not provide a quantitative guide to fair and dependable division of the available water supply, especially for those who would increase their

uses for irrigation. It does not contribute to wise, beneficial use, conservation, and the prevention of waste, as does our basic State law on soil resources. It does not afford a basis whereby the public may participate in guiding the development and use of water. Our expanding economy calls for a firm, positive policy of expanding beneficial use and conservation of surface waters.

The following adjustments in our existing common law of defined streams and lakes might well be considered as one means of encouraging better use of water:

1. Develop and incorporate into State legislation or constitutional amendments, or both, new basic water policies that contribute to beneficial use, conservation, and the prevention of waste; security of and encouragement for investments; wise administrative guidance in water development and use; and fair and equitable division of water supplies among present and potential water users under quantitative rules of guidance known to everyone.

2. Legislation implementing those basic policies, including definition of terms to clarify existing and new laws, limitations on or exemptions from the application of new laws, and definition of agency administrative responsibility and provision for administrative and other procedures.

3. Programs of research, education, and technical guidance that seek to encourage full development and use of the water resources of every State according to their capabilities and the needs of all the people.

The statutory systems for defined natural watercourses may be divided roughly into prescriptive, condemnation, and appropriative rights. All those rights, in effect, are of the appropriation type—appropriation meaning the right to divert and take possession of a given amount of water. But they are not generally recognized as such, at least in a technical sense.

Under the law of prescription, a person who does not have a lawful right to take water from a defined stream may acquire a right to do so if he takes water to which another is entitled and continues this use for the full statutory period, which may be as much as 20 years in some States. That right arises by adverse use above that of the rightful owner. Use below cannot ripen into an adverse use against a party above after the water has passed his lands, except in very unusual circumstances.

The prescriptive holder must take the water each year for the full statutory period under a claim of right, adversely to the interest of, and with notice to, the rightful owner. Thus, in this aspect of water law, the State sanctions a wrongful taking if it is continued long enough. The right so acquired is specific as to time, place, and amount, and therefore is more dependable than a common law right. Having once acquired the right, however, the prescriptive holder may not increase his use over that made during the statutory period, unless he seeks to acquire a new prescriptive right for an added use by the same long and hazardous process. The measure of his right is the extent of his actual use, unless the court allows the full capacity of a diversion ditch or reservoir, regardless of actual use.

Even so, before the holder of a prescriptive right can be sure as to the nature and extent of his right of use, he must have this ascertained in a court of law by the verdict of a jury. The nature and extent of use is a question of fact for a jury, just as is the question of reasonable use under the riparian system. And so there is uncertainty and expense in proving every element necessary to establish the right.

The important point to be considered is that greater artificial uses are being made of stream waters in the face of droughts and insufficient storage facilities—the very environment in which the law of prescription often comes into play. A permissive use, of course, cannot ripen into an adverse use in any case.

A difficult aspect of prescription is the fact that actual notice of the taking is not required. The party adversely affected is charged with notice under the law if he could have exerted (but did not) a reasonable degree of vigilance in ascertaining what adverse uses are being made upstream.

Some farmers are losing their rights of use under this system in places where water shortages exist. Others may be gaining new rights. The situation may increase in the future. But it might be argued that persons who are entitled to use the water but do not do so should not complain if others invest their funds and time in water development and so contribute substantially to rural living.

The better way to encourage beneficial use without waste might be to establish a system of appropriation that authorizes a lawful taking in the first place, requires public notice to existing holders of rights, and provides for the allocation of new rights only where and to the extent that they will not interfere with vested beneficial uses, except for public purposes upon payment of just compensation.

Rights acquired by condemnation for public use need only limited attention here. Municipalities and other organizations exercising public functions may be authorized by statute to acquire some water rights upon payment of just compensation. That is necessary to assure adequate water supplies for large groups of people. But individual farmers in most States have no such authority. Such farmers cannot move their lands to more favorable locations of water supply or water law, as can industries. They cannot condemn water rights and rights-of-way in most States, as can municipalities. In view of the unfavorable aspects of the law of prescription and condemnation as they affect farmers, the farmers in some States are at a disadvantage.

The other system of statutory law for surface waters is that of prior appropriation, which is prevalent in the Western States. It is the only system operating in the Intermountain States, but in some of the Pacific Coast and Great Plains States the riparian system exists in one limited form or another. The appropriation system grew out of necessity, born of water shortages and expanding artificial use of water.

Under the system of prior appropriation, a person who has lawful possession of a piece of land on which he can make beneficial use of water can obtain from the State a permit to divert and apply to use a given amount of water at a given time and place. Appropriation has been allowed as a part of the customary or common law in some States. The right does not arise by reason of ownership of land—only by beneficial use of the water.

Such an appropriator may use the water on land, whether it touches a stream or not, and whether or not it is within the watershed of the stream at the point of diversion except in a few States. But his right of use is limited by the principle of beneficial use, in which waste is not recognized as part of the right. If a water supply exists and other established rights would not be adversely affected, the permit must be granted unless some real and substantial public interest would otherwise be adversely affected.

The appropriator is given a reasonable time in which he may complete his diversion, conveyance, or storage works and apply the water to beneficial use. If he does these things diligently, he is entitled to a license to continue to use the amount of water covered by his permit. The appropriative right may be conveyed with the land or sold separately as any other type of real property.

If the appropriator fails to make beneficial use of the water for a relatively short period defined by law, he may lose his right of use. Others need the water, and only a limited supply is available. It must not be wasted. Furthermore, if the appropriator uses more than his allocated amount, he may be

enjoined by junior appropriators entitled to any water not required to satisfy senior rights. Those first in time are first in right, but beneficial use is the limit and measure of the right.

The system is much more dependable and flexible than the riparian or prescriptive systems. The right is specific as to time, place, and amount, and the taking is lawful from the beginning. The system has been gaining in favor over the years to the point where the riparian system is no longer important in most Western States. Some Eastern States have taken steps to utilize some of these principles of appropriation.

But the system is not perfect. The standards of beneficial use, adopted many years ago by the courts, are excessive in some Western States. Thus streams have become overappropriated when people ask for more water than they need. One of the major problems in the West is to increase the efficiency of water use and conveyance to the land and to reduce consumption by nonproductive vegetation. Standards of beneficial use ought therefore to be improved by new law and by voluntary practice. Eastern states could benefit by this experience.

Another problem is the inflexibility of the system in some States. The riparian system is inflexible and monopolistic in a broad social and economic sense. It is continuously contracting, never expanding. But the system of prior appropriation is inflexible to the extent that the rights acquired under it must be satisfied in most instances as to time and amount, regardless of the position of use on the stream. It is hard to distribute water under the law in localities where time of use varies markedly up and down the stream. Waste of water, loss of water, and increased costs of administration may be the result.

Suggestions for improving the statutory systems by legislative and other means might be offered in terms of:

1. Providing quantitative rules of guidance by use of some form of appropriation wherein a lawful taking is authorized from the beginning by statute or constitutional amendment under a broad basic conservation policy.

2. Reducing or abolishing the role of prescription, as other means of appropriation are made available.

3. Providing sound standards of beneficial use consistent with efficient use of water and land and the storage and conveyance of water.

4. Developing for unappropriated waters a more flexible system for time of delivery within a watershed or drainage basin which constitutes limitation on newly acquired rights. In places where waters have been appropriated, increase the flexibility of delivery time by adoption of voluntary schedules, tested from year to year until found to be dependable, then incorporated into agreements to continue the workable schedules.

5. Providing for limitations on the use of minimum stream flows, exempting domestic uses, and authorizing the establishment of reserves to meet future needs and to facilitate administration of water use.

Rights in ground water, as in diffused surface waters, arose under the common law by reason of the adoption of the theory that the landowner has absolute right to everything on and above his lands upward to the heavens and everything in and under his lands downward to the center of the earth. The theory overlooked an important, fundamental law of nature—the surface water above and the ground water below the soil surface is usually moving from a higher to a lower position.

To repeat: It is a basic principle of water law applied to streamflow that no one owns the water, as such, flowing in a stream. It is generally recognized as public water, subject to established rights of use. The landowner owns only a qualified right to take possession of and use some of the water under the conditions provided by the riparian or the appropriation systems. That is consistent with sound principles of the physical sciences that recognize the

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moving nature of water, which, after all, cannot be wholly ignored.

But the common law theory applied to ground water does not recognize that basic principle. The early English jurists who gave us this theory did not foresee the enormous uses of ground water that would be made by landowners in this century. They did not foresee the need for a public system of regulation when our economy of use of ground water became complex under conditions of shortage.

The common law system has two broad rules that vary from State to State. Under the strict rule, the only limitation on the nature and extent of use is the water supply itself or the cost of recovery and replenishment. Thus, in places where the rule is in effect, one landowner may pump his own well so as to drain off the ground water of his neighbor and the neighbor has no legal recourse to stop him. The result is progressive deepening of wells or pits and excessive costs of pumping. In some localities the extraction of enormous quantities of water leads to land subsidence, the encroachment of salt water, and the abandonment of existing uses. Their correction becomes almost impractical. Drastic and costly control measures are of help if a supplementary water source for artificial replenishment is available. Yet some States still cling to the old common law system in the face of serious depletion of ground water. Preventive measures adopted now would pay great dividends in States where ground water problems are not yet acute.

THE SECOND RULE, a modification of the strict rule, varies by States. It provides no limitation on the right of the owner to develop and use ground water below his land except if special conditions exist. A court may restrain an owner who develops and uses the ground water in a way that willfully, negligently, or maliciously injures his neighbor's water supply. He may likewise be restrained if he should convey ground water from his own place to another and remote place for use or sale there, if he thereby injures the water supply of a neighbor.

That is referred to as the reasonable use rule. What is a reasonable use must be ascertained by a jury, as a question of fact. A limited lowering of the water table alone may not be such an injury as to come within this rule. The lowering must be such as to cause substantial injury to the water supply of another. Such a guide is no more than a stopgap to meet special conditions.

The rule of reasonable use is really an exception to the strict rule of absolute ownership of ground water below a person's land. In California this exception is developed in such a way that the overlying landowner is recognized as having a right in common with other landowners in the same ground water basin. Thus, his right of use is limited by the rights of all other owners equally situated over the same ground-water basin. It has been held, however, that if the ground water is surplus to the needs of all overlying owners, some may be exported for use outside the basin. But this aspect is looked upon as an appropriation.

These two court-made rules for ground water do not apply to well-defined subterranean streams. The latter are subject to the riparian or appropriation systems, depending upon the State law in effect. As long as the ground water is adequate, the two common law rules, developed when the supply usually exceeded the need, are satisfactory for most situations. But when the supply is short, as it is in many areas of the Southwest and several industrial areas of the East, the old guides are no longer suitable. They provide no real basis for dividing the common supply and protecting dependent investments. A quantitative guide under some form of statutory appropriation is needed.

THE STATUTORY SYSTEMS for the control and use of ground water, aside from prescription, condemnation, and pollution control, which are not dis-

cussed here, take three main forms. The first provides for capping and control of the flow of artesian wells. Such legislation is highly beneficial in conserving water supplies and pressure and also in reducing waste of water or drainage caused by surface seepage. The system does not solve problems of ground water generally. In a few States the law is not enforced effectively.

The second statutory system provides for limitation on the extent of pumping permitted in a given area, licensing of well drillers, and gathering of water facts by the State. The New York law, for example, requires a permit to install or operate new wells in some counties of Long Island where the capacity of the new wells or of old and new wells exceeds 100 thousand gallons a day. Wisconsin has a similar law.

In Illinois the statute authorizes establishment by referendum of local water districts to regulate development and use of ground water within certain limits. Texas has a similar, but more comprehensive law. In States where the systems are in effect, certain exemptions are made as to use where the law does not apply. Agricultural or domestic use is a frequent exemption. The statutes offer control methods designed to avoid conditions of scarcity. They tend to prevent the severe conditions that have arisen in some States, but they are limited in scope and are less comprehensive than the basic appropriation statutes of some Western States.

The third statutory system, that of prior appropriation, has been adopted in some Western States, among them Utah, New Mexico, Washington, and Oklahoma. Beneficial use is the essence of the right, and priority in time gives the better right. Administration of the laws resides generally in the State engineer, but it may be based on determination of facts as to the existence of a defined ground water basin or critical conditions of use and replenishment. Permits and licenses, issued as in the case of appropriations of surface water, are specific as to time, place, and quantity. The license constitutes real property and may be conveyed in the same manner that land is conveyed. Thus the right, once acquired, is much more dependable than the common law right.

Many States, particularly in the East, need improvements in their existing systems of ground water law. A few changes are suggested here.

1. Adoption of basic ground water policies that emphasize beneficial use, conservation, and the prevention of waste; security for and encouragement of investments; administrative guidance at State and local levels in line with capabilities of the resource and the needs of the people; and the fair and equitable division of the water supplies among those in need.

2. Establishment of legislation to implement the basic policies so as to provide a quantitative rule of guidance in development and use, including definition of terms to clarify existing and new law, authority of agencies charged with its administration, and administrative and other procedure for the determination of uses and guidance of development.

3. Research, education, and technical services provided by and through the cooperation of local, State, and Federal agencies to help State and local people further implement basic policies.

Modernization of State water law takes place slowly at best. The drafting of legislation itself is only one of the many tasks involved. The major problem is obtaining understanding and acceptance of principles of law, which tend to limit what a landowner or group of owners may do with waters occurring upon or flowing over their properties. The corollary of this problem is determining the most practical manner in which authority to limit use of these waters is vested in and exercised by local or State agencies of Government.

As the economy of water use be-

comes more complex, regulations must be resorted to so as to protect both private and public interests. This regulation amounts to a degree of transfer of power from individuals to agencies of Government. It is perfectly natural for property owners to resist such transfer until they are sure as to how a new or improved system is going to work. The key to success in bringing about this transfer lies in keeping control of broad operating policies in the hands of the people who give up some of their powers over water.

In these circumstances a great deal of cooperative study, factual information, and planning is required to achieve understanding and acceptance of water problems and provisions of law required to solve them. Experience indicates that this can be accomplished best by the formation of State and local study committees (of farmers and others) that can concentrate on one major segment of legislation at a time. The task is so large in most States that it must be divided into segments—taking basic problems first, the solution of which affords a foundation for the whole superstructure of modern water codes. These basic problems vary from State to State, even though two or more States may have some common problems.

FARMERS CANNOT accomplish this complex task alone, however. Other water users have responsibilities, too—municipalities, the industries, recreation groups, and organizations indirectly involved. Those users must be given equal opportunities to participate if sound and equitable legislation is to pass and receive public acceptance. Furthermore, new policies and procedures incorporated in law present legislative questions. Thus, leaders of both houses of each State legislature should participate in the studies. Full participation of all interested groups from the beginning is very important.

Modernizing water legislation is only part of the total job. There must be well planned, organized, and supported programs of research, education, and technical and other services provided by local, State, and national organizations and agencies. A few such services concerning water law and administration are noted here.

1. Analyses, summary, and preliminary interpretation of the existing water laws of each of the 31 Eastern States, as to rights and organizations concerned with water use and damage.

2. Intensive study and appraisal of special use and damage problems in each of those States, as well as those of some of the 17 Western States, to identify major legal and administrative difficulties and how best to overcome them by constitutional amendment, legislation, rules and regulations, and other means.

3. Provision of special advisory services to and development of technical guides for the use of State water law study committees, based upon the experience of all States and that of other countries, in their consideration of needed water legislation.

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First and most essential we must know the physical realities which we face. Too long we have reckoned our resources in terms of illusion. Money, even gold, is but a metrical device. It is not the substance of wealth. . . . Soil, water, minerals, vegetation, and animal life—these are the basis of our existence and the measure of our future.—PAUL B. SEARS

Sharing the Financial Responsibility

Roy E. Huffman

The United States has developed its water resources to their present level through Federal, State, and local action. The greatest of these has been the last. The activities of individuals and local groups have been responsible for most of the development. Irrigation is an example. Only about one-fourth of the irrigated land in farms in the 17 Western States, as reported in the 1950 Census of Agriculture, was developed by the Federal Government, and the States have had a relatively small part in the great task of making water available for irrigation and other uses.

We can assume that the work and money of individuals and communities will continue to bulk large in efforts having to do with saving and using water. But now, more than ever before, we have to recognize that many projects and programs in the future will involve larger financial outlays and a wider use of technical skills.

The Federal Government therefore can be expected to shoulder greater responsibilities, while individuals and local groups will be less of a factor than in the past, when development was less expensive and involved fewer technical problems.

We can assume, also, that the States may be able to take a larger share of responsibility for some projects which are beyond the capacities of individuals or neighborhoods but which do not require Federal help.

Continued participation at the Federal, State, and local levels means that the sharing of financial responsibility will become increasingly important. That is so because few future programs can be developed by one level of public or private effort in isolation from the other levels of action. The scope will be such that the benefits accrue to many different public and private beneficiaries. Who should help pay the costs of the developments? How much should each beneficiary pay?

The problem of sharing the financial responsibility is complicated by two crucial factors that involve efficient utilization of our water: The multiple-purpose concept and the river basin concept.

The development of water for multiple uses means that costs must be shared among different classes of users as well as among different levels of Government. The development of water resources on the basis of river basins is usually an interstate situation, in which benefits and costs are not related specifically to either the National or State boundaries.

Besides the amount of costs and their incidence among beneficiaries, then, a major area of concern is with the adequacy of the institutional arrangements available for putting into effect a system of cost sharing.

Many of the benefits can easily be defined and measured. It is a simple matter to point to the beneficiaries who should pay for them. But some other benefits are harder to define and cannot be measured in terms of money. They are the extra-market values—the ones that cannot be priced by the market mechanism. They include the intangible benefits. Most of them are in the area of public benefits—they accrue to an indefinite segment of the citizenry rather than to individuals or specific groups. Many of the extra-market values have national significance, and the costs are shared by the Federal Government.

Much attention and some research have been devoted to the problem of measuring extra-market values. Sometimes the emphasis has been on finding a way to apply monetary units of measure to normally nonmonetary values. Sometimes attempts have been made to formulate nonmonetary units of measure for extra-market values. Some measure of extra-market values is essential if the financing of water

developments is to be shared fairly. A growing population and increasing emphasis on recreation and the other esthetic considerations indicate that the extra-market values will be more important in the future than they have been.

It is comparatively easy to define the beneficiaries who are direct users of water and to measure the extent to which they should share in the costs. Among them are irrigation farmers, hydroelectric plants, industrial firms, and householders.

Determination of the relative financial responsibility of the indirect beneficiaries, private and public, generally is difficult. Especially troublesome is the allocation of public benefits and costs among local, State, and Federal units of Government. The local, State, and Federal views of what constitutes definable public benefits differs for each level of social organization. Local public benefits are often quite obvious, and the citizens recognize their importance regardless of whether they share the financial responsibility. Public benefits at the State level are often less apparent and at the national level they are diffused and indefinite.

LOCAL PARTICIPATION in the financing of water projects has been carried out through several different institutional arrangements.

District organizations which function as legal subdivisions of the State and associations of water users organized as cooperatives are two common arrangements. The type known as the conservancy district has been widely adopted. The Muskingum Watershed Conservancy District in Ohio has done much to eliminate floods, increase the productivity of agricultural and forest lands, and create valuable recreational facilities.

The Muskingum Watershed Conservancy District was created in 1933. It involves 18 counties comprising about one-fifth of the State of Ohio. Creation of the District was a result of recurring floods in the area. The District began with substantial Work Projects Administration grants from the Federal Government but has been self-supporting for many years.

The manner in which the Brandywine Valley Association in Pennsylvania has controlled erosion and cleaned up a polluted stream is typical of the way in which local forces have organized to solve problems connected with water. The stream carried the topsoil from bare hillsides and gullies and was contaminated with raw sewage and industrial waste. The Brandywine Valley Association is made up of more than 800 dues-paying members. Widespread use of pictures of bad situations has provided a form of moral suasion which has caused those responsible to apply corrective measures.

The district type of organization has been used widely in connection with land drainage and irrigation. As a legal subdivision of the State, the district has taxing power and the financing is handled partly through the levying of taxes against the lands involved. The boundaries of drainage and irrigation districts are usually the same as the limits of the land area benefited.

There has been increasing recognition, however, of the fact that others than farmers benefit from drainage and irrigation projects. The existence of nonfarm beneficiaries has been noted particularly in connection with irrigation developments. That has led to the formation of conservancy districts in many new irrigation areas in order that other beneficiaries may be called upon to share in the financial responsibility besides the farmers who make up the traditional irrigation district.

The problem of identifying and measuring nonfarm benefits of irrigation at the local level has been the subject of several recent research studies. Much remains to be done in this area of research. Factual information regarding the nature and extent of local nonfarm benefits is essential to

the functioning of any institutional arrangement concerned with collecting from both farm and nonfarm beneficiaries.

The Northern Colorado Water Conservancy District came into being as a means of providing an adequate water supply to one of the oldest irrigation areas in the West. The Union Colony in 1870 settled on a tract of raw land that later became the site of Greeley, Colo. The economic growth of the area exceeded the water supply available for irrigation and other uses. The size of the development necessary to assure an adequate supply indicated that Federal participation was necessary and that other beneficiaries, besides farmers, should share in the financial responsibility. The conservancy district was organized in 1937 after the Colorado Legislature adopted the necessary enabling act. The conservancy district contracted to repay to the Federal Government 25 million dollars in 40 annual installments for the irrigation benefits created by the development. The rest of the construction costs were to be repaid by revenue from the hydroelectric power facilities, which are retained by the Federal Government. The irrigation costs are shared by all the beneficiaries in the district. A mill levy on all rural and urban property in the district will repay about one-fourth of the 25 million dollars charged to irrigation benefits. The other three-fourths will be repaid from acre-foot assessments paid by individual farmers, municipalities, irrigation companies, and other direct users of water.

The 83d Congress has authorized a program that involves a sharing of the financial responsibility for the water-conservation measures installed on small watersheds. A local group must declare its interest in a watershed program and share with the Federal Government in the cost of the development work undertaken.

The program involves 60 small pilot watershed projects as a means of finding out the best ways of securing local-State-Federal cooperation in planning and carrying out a watershed-protection and flood-prevention program. The program should also serve to demonstrate the benefits to be derived from such work. About 50 percent of the total cost will be borne by the Federal Government. Local people will receive credit for conservation and flood prevention already installed by them, and for the land, easements, rights-of-way, and cash they contribute to new construction.

Louisiana has a drainage program supervised by the Department of Public Works. The agency has assisted parishes (counties) in consolidating and rehabilitating existing drainage districts. An important phase of the program has been to improve the financing of the local drainage enterprises. The Louisiana Legislature has provided several millions of dollars for the Department of Public Works to use in improving and extending drainage facilities.

Besides working with parishes and local drainage districts, the Department of Public Works cooperates with the Federal Government in its major drainage programs. Thus the State coordinates local and Federal action, including financing arrangements. In addition to financial help given to local drainage groups, State funds have been made available for matching Federal appropriations for work on major drainage outlets.

A statewide irrigation program in Montana is carried out by the State Water Conservation Board, which was established by the Montana Legislature in 1934. Originally established to help solve problems associated with the drought of the 1930's, the Board has become an important and permanent factor in the development of irrigation projects. In 20 years the Board has irrigated 133,294 acres of new land and provided supplemental water for 252,920 acres of existing irrigated land.

More than 16 million dollars have been expended on irrigation projects developed by the Board. About one-

third of the funds came as Federal relief grants for labor and materials during the drought and depression years; about one-third was derived from water revenue bonds; and the legislature appropriated the rest. Most of the funds available in recent years have been the State appropriations.

No formal arrangement exists for others than the irrigation farmers to share in the costs of the projects constructed by the Board. The Federal grants were not reimbursable. The amount of the Federal contribution may bear little relationship to the national benefits that have flowed from the program of State water resources development. If the irrigation farmers repay in full the funds derived from the water revenue bonds and State appropriations, no other beneficiaries in Montana will have shared in the financial responsibilities for the program of development. If the State appropriations are not repaid in full to the Treasury, all the taxpayers in Montana will help pay for the indirect benefits of the irrigation projects. As in the case of the Federal contribution, however, this sharing of costs would be accidental and may bear little relation to the actual amount of the benefits to the State.

Some water programs create interstate problems. Increasing attention is being given to institutional arrangements—notably interstate compacts—that will permit the sharing of financial responsibility on a regional basis. An interstate compact is an agreement that two or more States enter with the consent of the Congress. They have been used for a variety of purposes, including the allocation of water.

Compacts may also be used to establish the financial responsibility of each State concerned with an interstate program of development. Unless some coordinated system for water development (including financing) is established at the Federal level for a river basin, it seems necessary that the States have some means for integrating their actions and for specifying the rights and responsibilities of each.

Compacts can be useful tools if the rights established are not so fixed that they prevent economic change and freeze obsolete patterns of resource use. Setting up an institutional arrangement to facilitate the sharing of financial responsibility among States in the development of water resources should not become a barrier to securing the maximum in benefits from water resources.

Cost sharing should tend to promote a feeling of responsibility on the part of local, State, and Federal taxpayers for the actions taken with respect to water developments. It is easy for taxpayers at one level of Government to favor a particular project if all or most of the costs are to be borne by taxpayers at other levels. But if the sharing of financial responsibility is to be accepted by the direct users of the resources, the individual and group responsibilities should be determined as accurately as possible.

It should be stressed that public benefits will continue to defy precise measurement. That lack is not a basis, however, for permitting the public share of development costs to be represented simply as a residue after private benefits have been determined and the costs allocated.

If financial responsibility for developing water resources is to be shared, it should be on a realistic basis. First, the share of costs to be borne by private beneficiaries should be determined. Second, the definable public benefits for which local, State, and National groups are to pay should be set forth. Third, costs which do not stem from private benefits or definable public benefits but are to be borne by the public are a subsidy and should be recognized as such and should not be confused with definable public benefits.

Because many public benefits will remain highly indefinite, it is likely that the taxing power will remain an important tool in the cost-sharing

process, particularly at the national level. It is impossible to associate many public benefits with any segment of the public or to reach any general agreement as to the exact importance of the benefits. And yet the national public will continue to be willing to share in the costs through acceptance of the idea that it is in the public interest. The exact extent of the public benefits cannot be measured any more than the benefits of publicly supported educational facilities or agricultural research can be measured.

The taxpayer accepts the development of water resources as worthy of his support because of a growing population, because it broadens the Nation's economic base, because it is deemed vital to national security, or for some other reason. Whatever may be accepted as justification for Federal cost-sharing, the public is entitled to know that other beneficiaries, public and private, are carrying their share of the costs.

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The Lord God took the man and put him into the garden . . . to dress it and to keep it.—(GENESIS 2:15).

The throwing out of balance of the resources of nature throws out of balance also the lives of men.

—FRANKLIN D. ROOSEVELT

Forests are diminishing, water resources are dwindling, wildlife is barely holding its own, and the battle to protect soils, though hotly waged, is yet in its early stages and far from being won.—FAIRFIELD OSBORN

He is the greatest patriot who stops the most gullies.—PATRICK HENRY

Teaching and Learning About Conservation

Charles W. Mattison

Water conservation, like any other subject, can be taught in schools and colleges. It need not be a separate course, but it can be taught by integration with the entire curriculum.

Like other subjects, it has three requirements: A popular demand that it be taught, teachers trained in subject matter and teaching methods, and adequate and accurate teaching aids.

The demand for the teaching of water conservation must come from the local communities. Few, if any, school administrators oppose the teaching of any phase of conservation. They are subject to pressures to teach many different things, however, and they can teach only the subjects that are considered the most important.

Some teacher-training institutions have recognized the need for training in conservation and include it in their regular curriculums. Some conduct conservation workshops in summer terms. More than 100 such workshops gave training to more than 4 thousand teachers in 1954. Some colleges offer extension courses in conservation.

Many good teaching aids are available—textbooks, booklets, bulletins, films, posters, charts, slides, photographs, and recordings.

One of the aids is this Yearbook. Many of its chapters can be used in the training of classroom teachers and in high schools.

The high school teacher of science, for example, will find useful the chapters on the nature of water and behavior of water, such as those that begin on pages 9, 18, 41, and 84.

The teacher of the social studies can make effective use of the chapters on the importance of water to human beings, pages 1, 35, and 171.

The teacher of vocational agriculture can link water conservation to farming through the chapters dealing with the importance of water to domestic animals, in irrigation, soil management, and so on.

The teacher of physical education can integrate the chapters on safe water (pages 615, 636, 649, and 655) with health instruction.

So it goes from front cover to back.

WATER, THE RESOURCE, is also a teaching aid. What can be better than the resource itself to help us learn about water and its conservation? Water, in some form or other, can be found anywhere people live. The lush lawns at the State capitol in Cheyenne, Wyo., are possible only because of the ample use of water. A teacher can take a class over those lawns and teach a great deal about the importance of water in making a community beautiful. Where does the water come from—from national forests many miles distant, and that is a subject for another class discussion. Why were the national forests established—to help guard the water supplies. That clear, cool water coming from the irrigation pipes to the grass in Cheyenne has great teaching possibilities.

Must teachers and students take long trips to use water, the resource, as a teaching aid? Do they need to view huge dams or great power plants to illustrate facts about water? Such structures should be used when they are reasonably nearby. But many simpler, closer, outdoor situations offer useful teaching material. For example, rain falling on a bare, compacted school ground illustrates the poor water-absorption capacity of that soil. Compare that and the rain falling on a nearby forest or pasture. Right there is illustrated the value of plants in helping to keep the soil porous so it can store water for future use.

Any stream is an excellent teaching aid. Study it firsthand. Does it maintain a fairly constant flow of water the whole year? Why? Is it dry in summer? Again, why? What is its importance to the community? Is its water clean? Here, again, the teaching potential of water is limited only by the teacher's imagination.

The use of water, the resource, as a teaching aid will require trips away from the classroom. Therefore some suggestions for conducting field trips have a place here:

Let pupils and their parents, if possible, help plan the trip.

Know the route well. Plan the schedule carefully.

Have enough safe transportation, whether it be school busses, parents' cars, or a public carrier. If any travel is on water, make certain that there is a life preserver for each passenger. Do not overload the boats.

Clothing should fit the season and the type of trip.

Allow time for rest periods. If meal time occurs during the trip, make sure there is a lunch for each student.

During the trip, explain fully each point brought out. Use maps, charts, and other supplemental material to help clarify discussions.

Encourage students to ask questions. Review the more important points before leaving the area.

Back in the classroom, test what the pupils learned on the trip. Ask questions. Allow them to discuss experiences. Are their attitudes about the conservation of water different from their attitudes before they made the trip?

LET FILMS bring water to the classroom if the class cannot study water in the field. Films are an effective teaching medium when the group is prepared before seeing them, and the films are followed by interpretation by both students and teacher. A motion picture film on water conservation, if shown to an unprepared group of students, often becomes entertainment rather than instruction. Adequate previewing preparation by students, joint interpretation following the showing, and subsequent evaluation through

oral or written tests are parts of the effective use of the motion picture as a teaching aid.

Films that help teach water conservation have been produced by public agencies, educational organizations, and industries allied with the natural resources. Without trying to be all-inclusive, I list a few 16 mm. sound, color films I have seen and recommend to teachers, classes, and adult groups interested in the subject.

Most of these films are available on free loan except for the payment of transportation charges. For some there is a rental fee. It is suggested that users write to the producer (whose name and address immediately follow the film title) for details on borrowing, renting, or purchasing films.

Adventures of Junior Raindrop. Forest Service, United States Department of Agriculture, Washington 25, D. C. 7 minutes. An animated cartoon of a raindrop's visit to earth.

Arteries of Life. Encyclopaedia Britannica Films, Inc., 1150 Wilmette Avenue, Wilmette, Ill. 10 minutes. Water and forests are portrayed as important elements in the chain of life.

Clean Waters. General Electric Company, Electronics Division, Electronics Park, Syracuse, N. Y. 21 minutes. The importance of unpolluted waters.

Lifeblood of the Land. Forest Service. 20 minutes. How we create wealth if we maintain the absorbent soil covering, and how we invite disaster if we destroy it.

Living Water Series, Parts I and II. Encyclopaedia Britannica Films, Inc. *Nature's Plan.* 14 minutes. How water moves from earth to sky in an endless cycle; how nature's storage system in the soil holds the water in place until needed. *Man's Problem.* 19 minutes. Sound watershed management as the important phase of water control. Dams are of little use if watersheds are neglected or destroyed.

Mountain Water. Forest Service. 17 minutes. The function of mountain vegetation in conserving and regulating water supplies.

Pipeline to the Clouds. General Electric Company. 25 minutes. Relates sources of water to the needs of people.

Raindrops and Soil Erosion. Soil Conservation Service, United States Department of Agriculture, Washington 25, D. C. 21 minutes. Raindrops on unprotected soil are shown to be the cause of much of our erosion.

Snow Harvest. Soil Conservation Service. 24 minutes. The important and hazardous activity of making snow surveys in high western mountains.

Thirsty Acres. Union Pacific Railroad, 1416 Dodge Street, Omaha, Nebr. 25 minutes. The reclamation of new land through irrigation.

Waters of Coweeta. Forest Service. 20 minutes. The results of 20 years of research work at the hydrologic laboratory on the Coweeta Experimental Forest in North Carolina.

Your Valley, Your Future. Connecticut River Watershed Council, Western Massachusetts Electric Company, 73 State Street, Springfield, Mass. 20 minutes. The cooperation of conservationist, farmer, industrialist, electric power worker in conserving water.

Watershed. Wisconsin Conservation Department, Madison, Wis., 24 minutes. Demonstrates good watershed practices in Wisconsin but has application to other eastern agricultural areas as well.

COLOR SLIDES are used extensively. Sets of slides relating to water can be purchased commercially, but they are a more valuable teaching aid when teachers and students themselves build them around local situations. In many classrooms, much of the work is done by student committees.

A good way to teach water conservation is preparation of sets of slides as a term assignment. One committee may write the water conservation story, another prepare the shooting script, and a third make or obtain the necessary props. Still another committee photographs the scenes, and a fifth committee writes the narration. The completed set of slides is shown to the

entire class and perhaps to the student body. Following that, the slides are available to other classes in the school.

Publications on conservation include many written for students. Others are valuable to teachers. Not all discuss water exclusively. Among them are:

Raindrops and Muddy Rivers, by Mary Melrose and others. National Wildlife Federation, 232 Carroll Street, Takoma Park, Washington 25, D. C. (Lower elementary.)

Water Appears and Disappears, by Glenn O. Blough. Row, Peterson and Company, New York. (Lower elementary.)

Billy Bass; Tommy Trout; Bobby Bluegill and others (9 books), by R. W. Eschmeyer. Fisherman Press, Inc., Oxford, Ohio. (Upper elementary.)

Water, Water Everywhere, by Mary Walsh. Abingdon-Cokesbury Press, New York and Nashville. (Lower elementary.)

Make Way for Water, by Eleanor Clymer. Julian Messner, Inc., New York. (Lower elementary.)

The Big Three—a Playlet, Forest Service, United States Department of Agriculture, Washington 25, D. C. (Teachers.)

Not Only for Ducks, by Glenn O. Blough and Jeanne Bendick. Whittlesey House, McGraw-Hill Book Company, New York. (Upper elementary.)

Water Supply, by Bertha Parker. Row, Peterson and Company, New York. (Upper elementary.)

Water—Wealth or Waste, by William Pryor. Harcourt, Brace and Company, New York. (Upper elementary and high school.)

Soil and Water Conservation, by Bernard Roth. Boy Scouts of America, New York. (Upper elementary and high school.)

Water, Land, and People, by Bernard Frank and Anthony Netboy. Alfred A. Knopf. New York. (High school and teachers.)

Waters of Coweeta. Forest Service, United States Department of Agriculture, Washington 25, D. C. (High school and teachers.)

Water—or Your Life, by Arthur Carhart. J. B. Lippincott Company, Philadelphia. (High school and teachers.)

Conservation of Natural Resources, Volume 7 of *Living Together in the Modern World*. Creative Educational Society, Inc., Mankato, Minn. (Upper elementary, high school, and teachers.)

Muddy Water, by Henrie Andrews Howell. Arthur C. Croft Publications, Division of Vision, Inc., New London, Conn. (Upper elementary.)

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Carl Rohwer, *The Hydraulics of Water Wells*, U. S. Soil Conservation Service Research, 15 pages (mimeographed), 1947.

Carl Rohwer, *Design and Operation of Small Irrigation Pumping Plants*, U. S. D. A. Circular Number 678, 78 pages, 1943.

Carl Rohwer, *Putting Down and Developing Wells for Irrigation*, U. S. D. A. Circular Number 546, 87 pages, 1940, slightly revised 1941.

Carl Rohwer and M. R. Lewis, *Small Irrigation Pumping Plants*, U. S. D. A. Farmers' Bulletin Number 1857, 30 pages, 1940.

C. F. Tolman, *Ground Water*, 503 pages, 1937, New York and London.

Ivan D. Wood, *Pumping for Irrigation*, U. S. Soil Conservation Service Research SCS–TP–89, 40 pages (processed), 1950.

What Research Is Doing on Problems of Water in Agriculture

Carleton P. Barnes

Many of us tend to take research for granted. We assume that someone has found out and knows just what to do to overcome a difficulty. Perhaps because we also have taken our water for granted, we are far from knowing how best to use and manage water in agriculture. But research is gradually overcoming this shortcoming in our knowledge. Much of the research deals with the complex relationships among water, plants, and soils. Whatever we do to one of the three nearly always affects the other two. In many of our experiments we must therefore measure multiple effects of what is done.

The problems of water in agriculture include not only those of getting and making best use of water on farms; they also encompass the problems of managing our croplands and pastures, forests, and ranges so that damage from runoff and floods is held at the lowest point practical, and that the sources of water underground or in streams are improved to the greatest extent feasible.

To HAVE ADEQUATE sources of water is one need that research is helping to meet. It aims to improve water supplies from sources at all stages in the water cycle from water in the atmosphere to water in the sea.

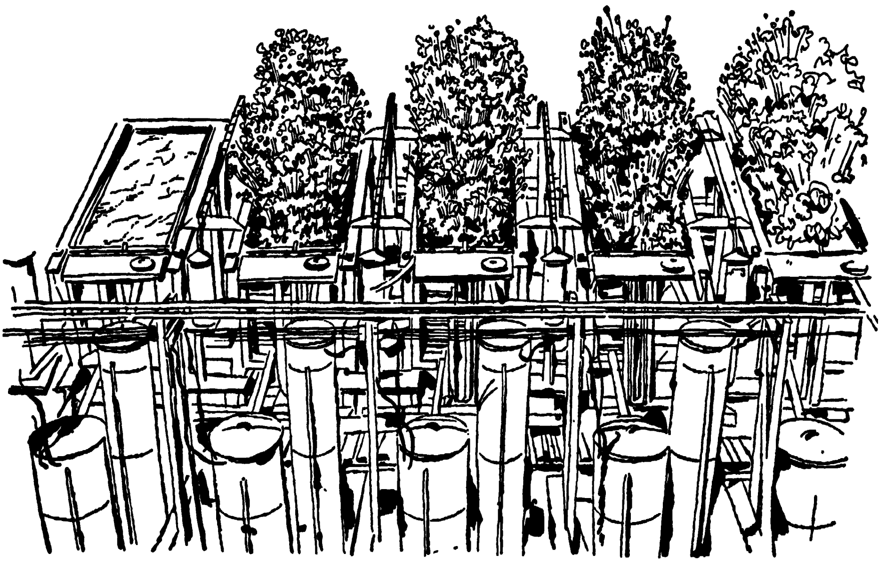
Changing the rains is the subject of another chapter in this book in which are described efforts to find out whether we can increase rain or snowfall at times and places where more is needed. Experiments have shown that precipitation can be increased under some circumstances by seeding clouds with various substances that act as nuclei for moisture to condense. Since most increases are obtained from clouds that might have produced rain anyway, the problem is to find out how much more rain can be produced by seeding than would have occurred without man's help. The problem is being studied from many angles, including research on the physics of cloud behavior. Results of the experiments do not yet suggest the possibility of breaking a serious drought. They do hold some promise of increasing supplies of water that can be stored in the soil or in reservoirs, or as snow, to reduce the severity of water shortages.

HOW TO IMPROVE THE SUPPLY of moisture getting into the soil from rain or snow is the object of much important research. The aim generally is to increase infiltration. On sloping soils this reduces surface runoff, the main agent of soil erosion. Therefore the research is almost equally aimed at soil conservation. Because surface runoff contributes to floods and to water supplies in streams, however, the research results bear on those problems, too.

Experimental plots and small experimental watersheds are used to find out what cropping systems are best for the dual purposes of increasing intake of water by the soil, and reducing loss of water and soil by runoff. Rainfall, runoff, soil loss, and crop yield are commonly measured. From some kinds of practices there is a cumulative effect over a period of years as a soil-improving rotation improves tilth and permeability of soil to water.

Some of the more elaborate experiments use lysimeter plots to measure runoff and the amount of water draining through the soil to lower levels. A set of weighing lysimeters at Coshocton, Ohio, is used to measure and automatically record all additions and losses of moisture to the soil. The instruments can measure a gain or loss of as little as .01 inch of water. Four-fifths of the moisture getting into the soil was evaporated or transpired by the crops, and one-fifth percolated down and out of the soil. Cultivating corn, by reducing evapotranspiration, noticeably reduced the rate of soil moisture depletion.

Because weeds and evaporation also



A battery of small lysimeters, instruments that measure the effect of plant cover on the movement of water over, in, and through the soil.

reduce the supply of soil moisture, all the research going on to find better and cheaper ways to control weeds is, in effect, research that may improve moisture supplies. The studies of cultivation and mulching practices aim at reducing loss of soil moisture. These practices do two things. They control weeds and also reduce the evaporation taking place directly from the soil.

In subhumid regions, like parts of the Great Plains, we use research to find ways to increase soil moisture supplies. For here rainfall is often barely enough to make a crop—in some years not enough. The soil must be made to catch and store as much moisture as possible. Cultivated summer fallow is a fairly old practice in the dryland wheat region. It works by keeping the land cultivated and free of growing plants for a whole season to build up moisture in the soil for the next crop. Research is going on to find out where other kinds of practices might be better than summer fallow, since there is no return from the land the year it is fallowed. At Woodward, in western Oklahoma, for instance, growing wheat every year, but preparing the land immediately after harvest and cultivating it monthly until seeding time, was found to give better results than fallow. Under other moisture regimes, soil conditions, or crops, the answer may be different.

Streamflow is a source of water supply for agriculture. But the amount and quality of water in our streams is also affected by the kind of management we give our farms and forests. We have noted that the kind of plant cover and the way we manage it affects the amount of rainfall getting into the soil. It affects the rate of runoff and so the amount of soil eroded, which in turn may further affect the infiltration capacity of the soil. It also affects the amount of water pumped out of the soils by the plants themselves, which in turn affects the capacity of the soil to absorb and hold subsequent rains. Because of these multiple effects of land management, we have experiments to find out what happens to the water that falls—and to the soil—when we manage land in one way compared with another. The lysimeter experiments mentioned earlier illustrate this

on a small scale. But when we turn our attention to the water supply in streams, we have to use experimental watersheds where streamflow can be measured.

Measurements of water yield from small watersheds with different soil, cover, and rainfall characteristics are providing data for the design of farm ponds, a source of water for stock, irrigation, fire protection, and recreation.

Experimental watersheds are being used to find out how to manage timberland so as to maintain or even augment usable water supplies. Usually similar pairs or groups of watersheds are selected and gaged for several years before any change in the timber cover is made. Then a change is made in one or more of the watersheds, and the measurements are continued until they begin to show what effects, if any, the change has produced. On a forest watershed in the Coweeta drainage in the western North Carolina mountains, for example, all of the trees and shrubs were cut down, but not removed. Reducing the amount of vegetation in this way so reduced the amount of water it pumped out of the soil that streamflow increased 65 percent the first year after cutting. Because there was no removal of logs or disturbance of roots, the increased amount of runoff did not result in more erosion. Nor were flood peaks any greater. This experiment was not made because anyone thought it would be good to cut off all the forest from our watersheds, but to find out how much the flow of streams would be affected by reducing the forest cover. It suggests the possibility that logging can be done so as to increase the usable water yield and at the same time allow the watershed to produce timber crops. It suggested other experiments, now underway or planned, which aim to find a set of practices that will allow the forests of that section to produce timber crops without impairing the production of usable water.

Experimental watersheds in Colorado are being used to find out how much the streamflow coming from melting snow will be affected by the way timber is harvested. Plot experiments showed that more snowfall was available for streamflow where timber was cut. But it would be disastrous to cut off all the forests in order to gain a little more water. Erosion would carry away soils and fill streams and reservoirs with debris. Timber and recreation values would be destroyed. The plot experiments showed further that some methods of harvesting timber caused more snow storage than others. So now the effect on streamflow and erosion of using these methods on an entire watershed is being studied, including the effect of building roads to remove the timber.

In most places, we have to strike a balance between managing the land to produce a timber or farm crop and managing it to reduce floods or increase water in streams. Where water is highly valuable and where a watershed will produce cover of only low value, such as chapparal, land will be managed mainly for the improvement or control of water in streams or ground water reservoirs. Where a watershed will produce a valuable crop, like corn, however, management will favor getting as much water as the crop can use into the soil where it grows even if this should result in less water in the streams. And it may favor growing corn, even though continuous hay or pasture might result in less runoff and flood damage, if the advantage of growing corn offsets these losses.

Research on watersheds is beginning to tell us how to manage crops, pastures, and woodlands so they will get the most benefit from the rain or snow that falls where they grow. It is telling us what effect this management has on the flow of water in streams. Thus, if it should be necessary to manage some watershed lands so that less water is consumed by plants growing on them in order to allow more to get into streams for consumptive uses, we shall have good evidence of the increased amounts of water in streams we can

expect, instead of having to guess. We shall also know how much offsetting disadvantage there is from management that permits an increase of soil loss and sediment in the streams. Arguments have arisen in the West, where water is especially treasured, concerning possible adverse effects upon supplies of stream water of land management that aims to increase range forage production. Research is under way to get quantitive evidence so we can deal with this problem wisely.

For example, comparisons of the use of moisture and the production of livestock feed by grasses and weeds on high ranges in Utah show that while weeds use the least water, they use it most wastefully. Weeds (dandelion-sweetsage) produced 80 pounds of green forage per inch of water used, while 3 grasses tested (smooth brome, Kentucky bluegrass, timothy) produced 135 to 350 pounds per inch of water. Total summer water use by evaporation and transpiration on areas covered by weeds amounted to 8.96 inches, as compared with 9.47 inches for areas covered with Kentucky bluegrass, 10.54 inches for timothy-covered areas, and 11.33 inches with smooth brome.

Some of the watershed experiments will provide valuable evidence to municipalities as to whether they should follow the rather general practice of complete forestation of watersheds, or use some kind of plant cover that will prevent erosion but consume less water than deeply rooting forest trees. The answer will not be the same for all situations, but will depend on the slopes, the depth and erodability of the soil, and the climate.

One of the results of watershed research is evidence on how much watershed management can be expected to reduce flood peaks. Preliminary results indicate important flood reductions on small tributary streams, but only slight reductions in floods on main streams. Studies have shown that a high percentage of the total flood damage over a period of years occurs along these small tributary streams, however, chiefly because there are so many miles of them. Much of this damage is to crops and other farm property.

Also, studies show that land management practices have a much greater percentage of reduction on the smaller, more frequent floods, than on the 100-year type. Thus the accumulative benefits add up over a period of time.

Not all watershed research is experimental. The continued measurement of streams, carried on by the Geological Survey, together with the continued measuring of precipitation, carried on the Weather Bureau, provide a means of relating streamflow to rainfall in watersheds of known dimensions and characteristics. The rainfall-streamflow relationships of watersheds differing in size, shape, land use, or other features can be measured. This provides data for estimating the yield of water from a watershed for municipal supply or for irrigation or the frequency with which flood flows of different sizes can be expected, estimates which are essential in the design of structures for storing water.

Water is lost after it gets into streams, reservoirs, and the irrigation ditches. Where water is scarce, as in the dryer parts of our Western States, research seeks economical ways of reducing the losses. Weeds, all the way from trees like saltcedar to aquatic plants, consume water in streams and canals. Some of them reduce ditch capacity. Different herbicides, as well as other means of controlling them are compared as to effectiveness and cost.

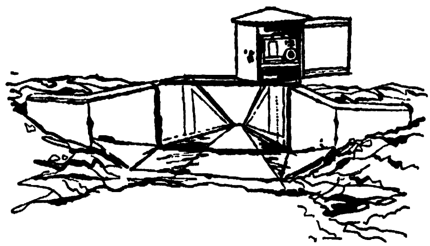
Irrigation water is also lost in conveyance through seepage and evaporation. So research tries to find ways of reducing seepage. Because of cost, lining the canals must usually be restricted to sections where losses are greatest. Seepage meters have been developed to help find the more porous sections of canals. Lining materials for ditches and conveyance structures are being tested for water tightness and other characteristics affecting efficient transportation of the water.

In laboratory experiments, films of certain chemicals, of a thickness of only one molecule, placed on the surface of a vessel of water, have greatly reduced evaporation. Whether this will have practical application in reducing evaporation losses from reservoirs depends on research yet to be undertaken in this country.

Sediment deposited in stream channels, reservoirs, and irrigation canals reduces their capacity for water storage and conveyance. In some places where this sort of problem is important, studies are made of the sources, movement, and deposition of sediment, as a guide to applying remedial measures. Methods of reducing bank cutting by streams are investigated so as to find practical measures to apply on streams where this is an important source of sediment. The research mentioned later on the safe disposal of runoff has reduction of sediment damage among its objectives.

Basic research on water and sediment behavior in ditches and other structures, at hydraulics laboratories such as that of the University of Minnesota at Minneapolis, is done to improve the design of water conveyance and storage structures.

Ground water is an important source of water for agriculture. Because ground water usually results from deep percolation of water infiltrated into the soil, some of the research mentioned earlier, aimed at slowing down runoff and increasing infiltration, will be of use in increasing the amount of water going into the deeper ground as well as into the supply of soil moisture. Not all of it will do that, however, because on much of our subhumid or semiarid lands soil moisture is used by plants or evaporated before any of it percolates to lower levels. In some places surface waters are spread on to porous beds above ground-water basins in order to replenish a supply of ground water that is withdrawn through wells. In a few places where it is desired to replenish ground water, no very porous beds exist, and research is trying to find ways to increase the rate at which finer textured soils will pass water through to lower levels. Mostly this involves trying different materials to make the fine soil particles flocculate into granules, thus creating larger pore spaces.



Weir and water stage recorder for measuring runoff.

Much as we depend on ground water, we still lack good knowledge of the occurrence and behavior of the different bodies of ground water. So measuring and exploring our ground water resources is a continuing research activity. Most of this is done by the United States Geological Survey and cooperating State agencies. Involved in or closely related to this program of measurement are many special studies to find out such things as how geological structures and kinds of rock affect ground water and its movement, the time and manner of recharge, the capacity and yield of particular ground water basins or units, and how ground water levels are related to streamflow. Studies are sometimes made of the basins where there is overdraft of the supply to find out the size of overdraft and what means there are to reduce it. One such study disclosed that water-loving plants wasted water in some places where the ground water level was near the surface and suggested the need to drain the land and convert the cover to something productive even if not less water-consuming.

Water quality, important nearly everywhere, takes on special signifi-

cance to agriculture in irrigation in the West, where waters of high salt content are quite common. Studies of sources of surface and ground water make it possible to tell whether water from a particular source is suitable for irrigation. The studies are tied in with experiments to find out what effects different kinds and amounts of salts in water have on soils and crops.

Reclamation of waste water may provide additional sources of water for agriculture. The problem is partly one of water quality, but research is also concerned with the mechanics and cost of safely reclaiming polluted waters for irrigation. Research by the University of California for the California Water Pollution Control Board has indicated that ground water recharge with waste water and, under some circumstances, direct use of waste water for irrigation, hold promise of augmenting water supplies for agriculture, especially in places where other supplies are scarce.

Fresh water from the ocean is the subject of another chapter of this book. It tells of research under way to find a cheap way of getting fresh water out of the sea. If this research is to be of much benefit to agriculture, it must devise a process much cheaper than any now known for desalting sea water. It is entirely practical now to produce fresh water from the sea for places at sea level which must have water and have no cheaper source. Curaçao, in the Dutch West Indies, gets its water from the sea by distillation. But agriculture cannot afford to pay as much for water as many industries and municipalities can. Even if an extremely cheap way was found of getting fresh water from the sea, the water would have to be transported uphill to most of the places that might use it.

How best to use water in agriculture is something else we seek to learn through research. The problem of increasing soil moisture by land-management practices that promote infiltration of rainfall and retard runoff was mentioned in connection with research on water sources. We can, of course, think of that problem as one of water use as well as of water supply. Because the same experiments by which we learn how to increase soil moisture frequently give us measurements of the runoff, and of the water yield of streams, it was convenient to mention it in the discussion of research on sources of water.

Soil fertility often determines whether plants take advantage of the moisture in the soil. Therefore virtually all experiments where we try to find out the effect on yield of adding more and more fertilizer are experiments aimed at using soil moisture most effectively. But getting enough plants per acre to use the available plant nutrients and the soil moisture is also involved. Experiments that try out different levels of fertilization in combination with different levels of plant spacing, seeking the most productive combination, have been very rewarding. Much of the increases in corn yield in the Southern States in recent years can be traced to this research. With moisture not a limiting factor, as under irrigation with an adequate water supply, even higher levels of fertility and plant population may be needed for highest production. So research undertakes to study the productivity resulting from combining various levels of all three—water, plant nutrients, and plant spacing. In fact, nearly all experiments where we try to find the combination of practices that will give highest practical production are aimed at the most effective use of water.

Irrigation provides opportunity for keeping soil moisture at about the levels that crops may need. Studies are under way to find out how best to apply the water, how much to use, and when to apply it. These problems have been investigated in the West over quite a period, but because there are so many combinations of climate, soil, crop, water quality, and surface relief, there remain many places where the best practices are uncertain.

We are beginning to learn from research how to time irrigations in relation to the stage of plant growth. Corn, for example, seems to need water most between the early tasseling and the silking stages. In an experiment in North Dakota, one irrigation during the period between early tasseling and silking produced 96 bushels an acre, while three more irrigations failed to increase yield. In similar experiments in some other places in the West, more than one irrigation was needed to get maximum yield, and in some instances later irrigations gave some increase in yield, showing the variation in research results from place to place.

The method of applying water in irrigation is also under experimental study. One furrow irrigation was found to remove as much as one-half inch of topsoil on many fields of beans and potatoes in southeastern Idaho because the streams in the furrows were too large. Comparisons of sprinkler and gravity irrigation are made to see which is the more advantageous under specified conditions. At North Platte, Nebr., for example, two alfalfa plots were kept at similar moisture levels, one with gravity and one with sprinkler irrigation. Each plot yielded 7 tons of alfalfa, but the sprinkled plot used 28.4 inches of water, compared with 32.6 inches on the other. That does not prove that sprinklers are better under all circumstances. In some places they may be too costly. Research seeks to find the circumstances under which a method is best.

How to keep irrigated lands from becoming waterlogged is another objective of research. The design of the water distribution system to avoid undue seepage is part of it. Provision of an adequate drainage system is another. Avoiding excessive water use is still another. In some places, however, leaching the soil with more water than the plants need may be necessary to remove injurious salts from the soil. Whether that can be accomplished depends on the quality of the water and the adequacy of drainage. Experiments deal with the delicate balance among those factors.

THIS PROBLEM of salt and alkali is acute in parts of our Western States. Irrigated lands have been abandoned in some places because of salt and alkali accumulation. The remedy is not a simple matter. It has been found that if a high percentage of the salts in soil or water are those of sodium, some soils tend to freeze up—that is, they become very slowly permeable so that leaching out the salts with ordinary irrigation water is difficult. Certain chemical amendments have been found to replace some of the sodium in soils, thereby promoting better permeability, but their use is practical only where there are means of draining the soil and where the irrigation water does not continue to supply large amounts of sodium. Some research into the way water moves through soils has begun to help solve these problems. The complex chemistry of salt-affected soils also is being studied in the hope of finding better remedies for the difficulties. Studies also are made to find out the extent to which different salt concentrations cause lower yields of various crops.

Large new irrigation developments, like the one in the Columbia Basin in central Washington, are served by experiments especially designed to guide irrigation where previous experience has been lacking. Development farms are selected in typical areas and experiments are conducted on them to discover irrigation methods and cropping systems that are most productive for the kinds of soils they represent.

More and more irrigation is coming into the humid regions. The benefits of using it to provide moisture in droughts are well known. But it presents a few problems not common in arid regions. One is how to prevent waterlogging of soil or serious erosion, when a heavy rain follows soon after an irrigation. Research is tackling this problem as well as that of how to manage and fertilize crops so as to get the most advan-

tage from the added water. It attempts to find out the conditions where sprinklers are advantageous and where surface irrigation is more practical. It is investigating the advantages of different water sources—wells, farm ponds, flowing streams—under given circumstances. It is concerned with problems in the design and operation of irrigation equipment. Irrigation is not necessarily advantageous under all circumstances in the humid areas. Much depends on the cost of developing the the water in relation to the acre value of the crop. Research is used to find out the circumstances under which irrigation is likely to be advantageous.

DISPOSAL OF EXCESS WATER receives special attention in many places. Sometimes that involves improving the drainage of lands that remain wet too long. Again, retarding runoff so it causes less damage to soils and contributes less to floods is the main problem.

Drainage experiments have been started to find effective and economical means of removing excess water from wet lands. The suitability of different kinds of drainage—tile, mole, open ditch, and surface drainage—under different situations, is studied. The best depth and spacing of drains is sought. Surface drainage to prevent excess water from entering the soil has shown promise in some places as a means of avoiding more costly drainage procedures. Giving a slight grade to fields of sugar cane in Louisiana having slowly permeable soils, for example, so water could run off more quickly, markedly improved yields.

Because there are poor soils and good soils among our wet lands, an important aim of the research is to find how much yields are increased by the different drainage methods investigated, so we can be sure the increased value of crops will justify the cost of drainage. Reliable guides are sought for draining the extensive wet lands of the Atlantic and the Coastal Plains especially, as they include one of our important sources of additional cropland for the future.

Research also seeks to improve the drainage of some soils by reversing deterioration of soil structure that reduces the permeability of the soil. Heavy farm machinery has contributed to this deterioration through soil compaction. Loss of organic matter during long-continued cultivation may also have impaired soil structure and permeability. Better cropping systems, improved farm machinery, and soil amendments that might improve soil structures are used experimentally to find ways to overcome the difficulty.

SAFE DISPOSAL OF RUNOFF is a problem research is seeking to solve. In many experiments we measure the effects of various practices on soil loss as well as on runoff. New cropping systems and tillage practices are compared with those commonly used. For example, wide-row spacing of corn, with legume-grass strips interplanted, is tried out in the Midwest to find out if the practice will reduce erosion without much sacrifice of yield. Research showed that lister planting of corn between terraces reduced soil loss 65 percent, with a 42 percent decrease in runoff, on the erodable loess soils of western Iowa.

Runoff-retarding structures are often needed to lessen soil erosion by water. They include terraces and their outlets, diversion ditches, and gully-control structures. Improvement in the design of the structures is always being sought. The performance of different kinds is tested in field experiments, where their combination with vegetative measures can be studied. Some of the more basic problems of design are attacked in hydraulic laboratories.

Earlier we noted how research in watershed management bears on flood reduction. We saw how nonexperimental hydrologic research, based on systematic measurement of precipitation and streamflow, gave data for predicting flood occurrence, and hence for the design of flood-control structures. Experimental research on the design of flood control structures, using hydrau-

lic research facilities like those of the St. Anthony Falls Laboratory of the University of Minnesota, continues to give us better means of preventing flood damage to agricultural and other property in flood plains.

"WILL IT PAY?" is often as important a question for research to answer as "Will it work?" The critical problem in getting fresh water for agriculture from the ocean, we saw, is to develop a process cheap enough that water can be got from the sea at less cost than it would take to bring it from natural sources. The same principle runs through nearly all problems of the control and use of water.

Records of the costs and returns from research-developed practices are therefore an important part of the research job. But economic research on the use and development of water is not limited to keeping records on experiments. Some farmers try new practices although no investigation has been made to see whether they paid. Farmers in the Eastern States who pump water from a stream or pond to irrigate their crops are an example. Whether the practice pays depends on the cost of getting the water and the pumps and pipes to apply it and on the amount by which returns are increased. But these are things on which each farm is apt to be different from another.

Economic research, by analyzing the experience of many such farms, tries to find out the circumstances under which the increase in returns have been large or small. Knowledge of these circumstances can help other farmers to make decisions on irrigating without running so much risk.

Economic research on water development and use is called on to answer not only the question "Will it pay?" but also "Whom will it pay?" "How much?" and "When?"

Storage reservoirs and other works for the use and control of water sometimes are built by agencies of Government—local, State, or Federal—rather than by individual farmers, when the undertaking is a community problem. Studies are made as to how the cost of such public works can be shared fairly among the benefitting groups. Studies that compare the ratio of benefits to costs of different plans for water use and control are made to aid in choosing the alternatives that provide the highest net benefits, taking into account how soon the benefits accrue. Studies are made of the ways our different State water laws facilitate or hinder water use in agriculture.

WE MUST NOT LEAVE the subject of research without pointing out the value of our nationwide system of soil classification and mapping in extending research findings. Without it we would have to try out experimentally all new practices, like those involved in drainage or irrigation, on almost every field, before we could be sure of their feasibility. With it, we at least know where the soils are similar to those on the experimental plot or field, and can have some assurance that a new practice will not fail because of a difference in the soil.

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Research, a Key to the Future

Robert M. Salter and Omer J. Kelley

Research is the father of progress. The advancements of today were seeded by research years ago. The developments of tomorrow are the offspring of research planned today. This is true for many aspects of business, medicine, agriculture, and other activities of man—and water.

Known problems that must be solved by research, if efficient use of water for agriculture is to become a reality, are of three general types:

Research having to do with problems of water that pertain to all agricultural lands;

Problems that are related to crop production; and

Research on watersheds.

BASIC RESEARCH in water relates to the efficiency with which plants use water; the nature of the soil moisture reservoir and its capacity, replenishment, and discharge; and the meteorological aspects.

The degree of efficiency of use of soil water by plants is governed by the rate at which plants transpire water while producing a unit amount of growth; the ability of the plant to grow under adverse conditions of water supply; and the capacity of the roots to penetrate the soil mass and absorb water.

How greatly crops vary in their rates of transpiration is exemplified by millet, which produces a pound of dry matter with only 300 pounds of soil moisture, and alfalfa, which under the same conditions would use about 1,000 pounds of water. Some plants wilting seriously, dry up, and eventually die in a long drought. Others suffer only moderate wilting and curling of the leaves and resume vigorous growth when soil moisture is replenished.

We need to know much more about the physiological processes that enable plants to persist during serious water deficiency and any genetic factors that may be involved in this attribute. We need research that will aid plant breeders to develop varieties having improved capacity to persist through serious droughts with a minimum of adverse effects.

Availability of water to plants in saline soils may be seriously impaired because of the increase in osmotic pressure of the soil solution. The physiological genetics involved in the tolerance of plants to such conditions is little understood, but improved salt-tolerant varieties are needed.

Relatively little is known of the relationship between degree of soil moisture depletion and the growth of crop plants in their various stages. We especially need to learn the net effect on crop production of wide variations in moisture stress during various phases of growth. Selection of varieties especially tolerant of wide ranges in moisture stress during critical periods of growth would be of decided economic importance.

Correspondingly, information is needed on the capacity of plants to withstand the adverse effects of wet, flooded soils that tend to asphyxiate roots because of poor aeration.

The roots of grapevines in the San Joaquin Valley of California may penetrate to a depth of 40 feet. Roots of potatoes in the same area may be confined to the surface 2 feet of soil: The ability of roots of a given variety of crop to penetrate the soil may make a tremendous difference in the size of the soil moisture reservoir drawn upon. Roots of Bermuda grass proliferate intensely and seem to permeate every part of the soil mass. Roots of celery proliferate rather poorly. Breeding to develop more effective root systems may be a way to enhance the ability of crops to use water efficiently and thus to withstand drought.

Information also is greatly needed about the rate at which water will

move into a unit area of a given kind of root when held in the soil by given levels of retentive forces: What is the range in the pulling power of roots of crop plants for water against the retentive forces in the soil? How is this pulling power related to the growth potential of the plant?

The capacity of the soil moisture reservoir is determined by the total mass of soil in the effective root zone on a specified crop and the amount of available water that may be held by a unit mass of such soil. Thus, plowsoles, claypans, and other impervious layers that restrict root penetration also limit usable capacity of the soil moisture reservoir. The water supply available to crops on many problem soils may be increased when research shows farmers how various management practices and tillage operations affect the ability of crop roots to penetrate to the deeper horizons.

Some terms that we use to describe soil moisture are not yet precise enough. We use "available range" to define the difference between the percentage of water held at field capacity and that held at the permanent wilting percentage. But field capacity is not an exact measure of amount; the value of the concept depends on the methods and conditions of measurement. It is a useful idea in management of soils, however, and more research should be directed toward the quantitative evaluation of field capacity or some comparable soil moisture constant. There is evidence that permanent wilting percentage in some soils corresponds more closely to a moisture tension of 4–6 atmospheres than to the more or less accepted measure, 15 atmospheres. We need complete information on the moisture tension in various soils that corresponds to the lower limit of readily available moisture for different kinds of plants.

Much of our irrigation practice is based on the concept that the soil water held within the available range, regardless of where within the range, is equally available to all crop plants. Some evidence that does not substantiate this view has been set forth. Because availability of soil water is a key in irrigation, we need precise data on just how available is the water over the available range in terms of growth by various plants and how it is modified by the type and condition of the soil. Furthermore, we know dissolved salts in the soil solution affect availability of water through their effect on osmotic pressure of the soil moisture, but we need more information on the response of crops to water availability impaired by salts, as compared to surface-force action of soil particles.

Replenishment of the soil moisture reservoir is the key consideration in irrigation agriculture, but it is no less important in the nonirrigated areas of both dryland farming and farming in humid regions. It involves a complex of factors that affect the movement of water into and through soil: Quality of water, soil mineralogy, chemical characteristics of the soil, structural aspects, including stratification, energy relations of the soil water, and hydrology of ground water. The interrelationships need to be investigated thoroughly in order that farmers and technicians can understand better how they affect the entry of water into soil and movement through it.

Excessive runoff during rainstorms, with the associated erosion and floods, is related directly to the rate of infiltration. So is the recharge of our supplies of ground water. Also contingent upon the rate of infiltration are cropping systems on slopes, ponding in rolling fields during rainy spells, the design of terraces, the construction of upstream flood-control dams, the design of the sprinkler irrigation systems, management practices under dryland farming, and the design and operation of surface irrigation systems. Yet available means of measuring rate of infiltration are unsatisfactory. In this, as in many other phases of research, we need devices and methods that will give accurate measurements in the fields.

We need this type of information

for another purpose, too. Downward movement of water through the soil performs an important function besides that of replenishing the soil moisture reservoir. It also removes harmful accumulations of soluble salts that may accrue from heavy fertilization or irrigation.

Needs for research related to crop production on farms may be divided into problems affecting irrigation, dryland farming systems, and humid and subhumid conditions.

Under irrigation, the research needs that are related to crop production include problems associated with water supply; conveyance; application, including time, method, and amount of irrigation, and efficiency of application; and drainage of excess water.

Discharge of water from the soil moisture reservoir is no less important than replenishment. Loss of water from the root zone takes place through two avenues—plant roots and downward percolation. Our evidence indicates that even when the soil seems to be permeated thoroughly with rootlets, less than 1 percent of the surface of the soil particles may actually be in contact with the roots. When roots deplete the moisture in a soil, more than 90 percent of the water molecules have to move over the surface of soil particles to the root surface. The rate of water movement in soils at moisture contents below field capacity is considered to be negligible, yet adequate movement has to take place. We need a quantitative study of this phenomenon in order to understand how much soil moisture is available to plant roots.

The downward percolation of water is the key to alleviating high water tables, water-logged soils, and the leaching of excess soluble salts. Drainage operations still are generally set up on a rule of thumb basis. This important field of effort therefore needs to be supported by fundamental research that will provide methods of evaluating accurately the facility of water movement and related factors that affect drainage.

Meteorological aspects affecting agriculture need to be clarified.

With regard to cloud seeding, in testimony concerning Senate Bill 285 of the 82d Congress, the National Science Foundation reported: "Recent developments in studies of cloud nucleation and in experimental seeding of supercooled clouds indicate that significant artificial modifications of weather may be possible. Current studies, as supplemented by field experimentations, do not afford a satisfactory basis for belief that widespread practical applications of weather modification efforts are feasible at the present time. . . . The greatest need at the present time is for additional basic research in cloud nucleation processes. Such basic research should go forward both in the laboratory to gain an understanding of the nucleation processes by which moisture condenses, and in the field to investigate natural processes of cloud nucleation. Controlled field experimentation, applying the knowledge thus gained to more effective understanding and practical use of cloud nucleation, is also necessary and desirable."

Special attention also should be given to weather data. Of special interest are such storm characteristics as duration, amount of rainfall in given periods, areal distribution of rainfall, and seasonal occurrence in different climatic or physiographic regions. The possibility of developing a method of expressing storm frequency in relation to areal distribution should be investigated. The information would be of great practical value in developing reliable estimates of peak flows and water yields for watersheds where adequate records do not exist.

Research is needed on ways of improving the accuracy of short-range and long-range forecasts. This will involve a better understanding between the upper air level circulation and rainfall. High-speed computing machines are needed for accurate forecasting.

Four major droughts have occurred in the Great Plains since 1880. Each of the first three was followed by a wet period. Information is needed on the occurrence of dry and wet periods on the Plains. Reliable forecasts of such periods and their duration would help to plan their operations better.

The cost of extracting fresh water from salt water by the basic existing processes exceeds the outlays that are considered economically feasible for extensive use in supplying irrigation, municipal, or industrial water in the United States. Further research is needed, based on results obtained on the work now under way and on new proposals based on hitherto unexploited phenomena of the behavior of water—vapor compression distillation, electric membranes, osmotic membranes, solar distillation, low-temperature difference distillation, and critical-pressure devices. Depending on results of initial research, additional development may also be required in freezing methods, solvent extraction, and conventional distillation improvements. Other research on which work may need to be undertaken includes ion exchange substances, osmotic membrane units, and the use of geothermal solar and wind energy.

Better methods are needed for predicting water supplies, with respect to the amount of water available any given year, the time of availability, and the quality and stability of the supply over a period. Particularly are they needed in the more humid areas, where irrigation water may depend on surface storage on the farm or on small creeks or rivers. What is the effect of farm storage and use of water in creeks and small rivers on the flow and availability of water farther down in the larger streams? Does it affect water tables in the immediate or other areas? How much of the water can be used, and when, without impairing other water rights? Answers to the questions must be available before the maximum use of water can become a reality. Farmers cannot afford to develop irrigation systems unless they know the amount and stability of the water supply, and their water rights are assured.

Ground water is used extensively in the West. In some places an overdraft of ground water has caused great economic loss; in other places, ground water resources have been neglected; the ground water is not utilized, although much money has been spent to provide storage in surface reservoirs. In some areas where serious drainage problems exist, the utilization of ground water for irrigation would do much to provide better seasonal distribution of water supplies, through exchanges that would make water available for additional acreage of lands in need of supplemental water and would materially lessen the drainage problem.

Research is essential to determine the feasibility of pumping, the extent of the ground water, and the effectiveness of pumping on the control of the water table. That research should include the recharging of ground water from areas where the ground water has been overdeveloped. The lack of adequate research is a primary reason for the overdevelopment of many of the ground water areas and their underdevelopment elsewhere. Many problems need careful study before general recommendations are possible.

They include: The feasibility of pumping in specific areas as influenced by occurrence, permeability, and extent of ground water aquifers; depth of the water table and depth of the aquifers; effect of pumping on control of ground water drainage; quality of ground waters. Other problems are the effect of pumping on existing water rights; hydraulics of wells, including the basic economic principles that apply to the development of ground water supplies; methods of increasing infiltration and permeability of water through the soil and methods of recharging underground reservoirs; and methods of preventing the intrusion of salt.

Problems of water conveyance occur wherever irrigation is practiced. In irrigated regions of the West where water is conveyed primarily through canals, at least 25 percent of the water may be lost through seepage from the time water is taken from the river until it is delivered to the field. Water so lost would be enough to irrigate an additional 6 million acres of land—a loss to the potential user and often a major cause of damage by the creation of high water tables. Ways must be found to reduce the losses. In some areas, water is conveyed by pipe or conduit. These methods are expensive. Other methods that need to be explored include the use of terrace and contour systems for conveying and distributing the water.

The application of water is a major concern to a farmer. The consumptive use of water and factors affecting it for the various crops must be known, because they determine the amount needed to produce the crop and because they are important in establishing limits on designs of irrigation system. Information is needed on total consumptive use, the daily rates, and soil moisture status and relationships. That information should make it possible to predict in advance the time of irrigation if no rain falls. In areas of good rainfall, accurate short- and long-range forecasts are essential to good irrigation practices.

Soil-water-plant relationships must be evaluated in order to know when to irrigate, how much to apply, and at what rate. They vary with respect to crop, soil, and climate. Few basic data are available on factors as they affect the infiltration rates which may vary as much as several hundred percentage points according to soil, season, type of crop cover, and cultural and management practices. Yet irrigation systems must be designed with the infiltration rate as one of the determining factors. It is important therefore to know the factors that affect infiltration and how to maintain the rate in a desirable range.

The drainage of excess water from soil may be of great importance anywhere. In the irrigated regions farmers often find it hard to separate the drainage problem from the saline and alkali problems, which usually are connected with drainage difficulties. That is not always the case, however. In many irrigated lands of the West, the underground drainage is insufficient to provide free flow of water, and the buildup of water table results. That almost always increases the salt and alkali content of the soil. Drainage is an essential part of every successful irrigation project. Ground waters accumulate in the lower areas of nearly all irrigation projects, except in a few places where natural drainage into deep rivers, channels, or tributaries is adequate.

On some 30 million acres of wet land in the South and in the Midwest we may encounter drainage problems that require a greater emphasis upon basic research in the field of soil-water-plant relationship. The application of the findings to given site conditions and their reduction to practice, however, will be necessary, because the removal of water from soil depends on its characteristics. Local conditions will determine which method of drainage is most effective. Pumping from wells has been effective and economical means in western areas where conditions permit their development. More information is needed to determine the degree of success to be expected before a well is installed. Further data are needed on the effect of various gravel filters and the effect of variations in back-filling techniques.

We need to know more about the wisdom of draining some wet lands—whether it might not be better to regard them primarily as potential producers of wildlife.

Needed research on dryland agriculture pertains to problems of moisture conservation and efficient use and the control of erosion. Because moisture often is the primary limiting factor in crop production in many of the

dryland areas in the West, studies should aim at finding more efficient methods of getting water into the soil and reducing loss in storage. Keeping the organic matter of the soils at optimum level is allied to the infiltration rate, water-holding capacity, and the reduction of runoff. In many parts of the West, 60 to 70 percent of the rainfall may be lost in evaporation. There is need for studies on the use and conservation of soil moisture. They should include efforts to develop cropping systems and tillage practices that will provide for most efficient use of water and efforts to select or breed crops that have lower water requirements and utilize moisture when it is available.

Conservation of water and the handling of excess water are the primary problems on which research is needed in humid and subhumid regions. Even though precipitation there provides more water than crops use, its distribution or intensity is such that periods of drought generally exist in parts of the growing season. The first problem is to increase the infiltration rate so as to get more water into the soil. We need more information on the role of specific crops, rotations, surface mulch, and cultural practices in increasing infiltration rates and on the effect of varying degrees of leveling, terracing, and land forming on retention of water and intake rate. With modern machinery, sufficient fertilizer and soil conditioning plants or chemical agents, what degree of leveling is possible on highly developed soils? What are the economies of such practices?

In parts of the humid area, certain times of the year are wet and others dry. Farmers need crop plants that will tolerate wet conditions and plants that will withstand dry conditions. Crops should then be planted according to their water requirements. Little research has been conducted along these lines.

Research pertaining to watersheds is concerned primarily with measuring and understanding streamflow and water yield and sedimentation. The purpose is to enable people to manage a watershed properly with a view to minimum peak flow, maximum water yield, and predictable water supply.

On a well-managed watershed, it should be possible to predict peak flow from a given type of storm and the frequency of various peak flows.

The rate of movement of water into and through the soil—to repeat—is of major importance. Infiltration rates frequently are lower than precipitation rates, and runoff occurs before the root zone is filled. Basic research is needed, as we have indicated, to find ways of increasing the infiltration. If more water enters the soil, less will run off immediately, and the peak flow of the stream into which the land drains will be reduced.

Research is needed on the effects of different types of cover with respect to its ability to intercept and hold the precipitation and with respect to its ability to improve infiltration rates.

Research is needed to determine the effects of terracing, contouring, land forming, and waterways have on the water-intake rate of soils, runoff, and peak flow. A small runoff on one farm may not be important, but it may become so downstream when multiplied by the number of farms on a watershed. It is important to know the effect of different species of trees and their age, density, and logging and other management practices on interception of water and snow, runoff, and total yield of water. The factors affecting the total yield of water are like those affecting the rate of streamflow, there are some different aspects of the two problems. In areas where there is a great demand for water downstream, water users sometimes ask whether conservation practices put into effect upstream will cut total water yield to their detriment.

The need for study of sedimentation in watersheds is reflected by the great damages that occur when eroded materials are carried into stream systems and when they are deposited in river

bottoms, city streets, storage reservoirs, or elsewhere. One must know the erodibility of the soil under the various conditions of rainfall, cover, slope, velocity of flow, and management practices. Erosion of streambeds and bank erosion are additional problems for which causes and corrective measures have not been fully learned.

Transportation of sediments is determined by type of material, size, dispersion, and velocity of the stream including its turbulence. Research is needed on the various factors affecting stream load and its deposition.

Many of the problems of deposition are associated with those of erosion and transportation. Engineers do not yet know as much as they need to about rate and pattern of deposition and the density deposited material. It should be recognized that the silting of lakes, reservoirs, and ponds is of major importance to agriculture. Engineers need additional information so as to make useful predictions of proper allowances for sediment when they design reservoirs.

Data on the yield of sediment should be obtained for the various watersheds. The details should be correlated with conditions of erosion, topography, soil, channelization, size, and other watershed characteristics. Such information is essential for site selection and design of needed control structures.

A CHARACTERISTIC of watershed research is that it is long-time research. Like research in dryland farming, it must sample the climate, and this requires time. It is also a type of research that cannot cover all local conditions. It is therefore important that the basic factors and their relationships be determined in order that the extrapolation or prediction values may possess the necessary degree of accuracy.

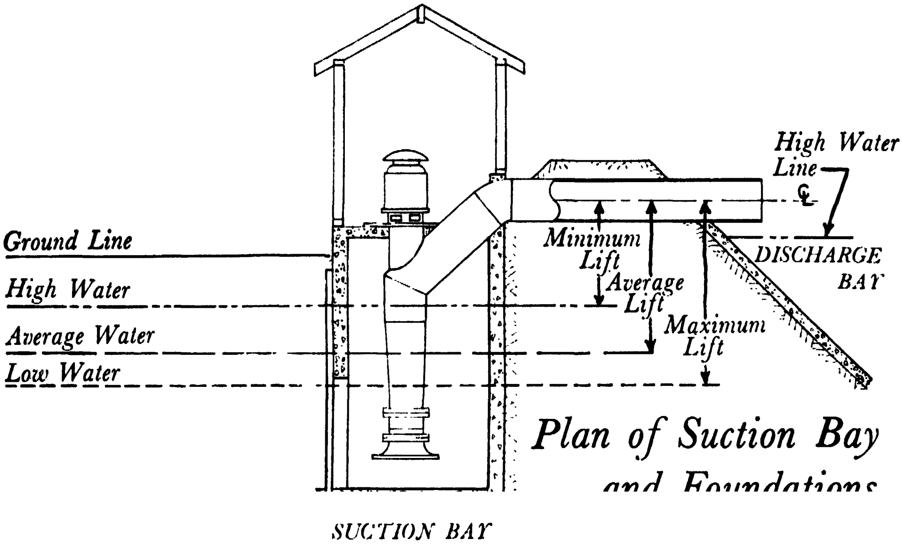
Further research in hydraulics will enable the development of low-cost structures for handling water. Where information is lacking, there is the danger of overdesign, with its resultant high cost, or underdesign, which results in failure. Specific research needs are related to water flow retardation, including erosion-control structures, such as drop structures, waterways, culverts, and cantilever outlets; water-storage facilities, such as farm ponds and irrigation reservoirs; irrigation and drainage structures, including canals, ditches, check dams, weirs, spiles, flumes, and other measuring devices; and sediment traps.

Water is one of the many items the farmer has to deal with in managing his farm. He cannot make major changes in the use and conservation of water without other shifts in management. If an adequate research job is done, all of these must be considered, and the best overall plan worked out along with its economic aspects. The putting together of the various results of specific lines of research into an overall management system in itself involves research. This type of research can best be handled with the use of pilot farms. This gives an opportunity to fit together the best combination of practices and to determine the most economic system.

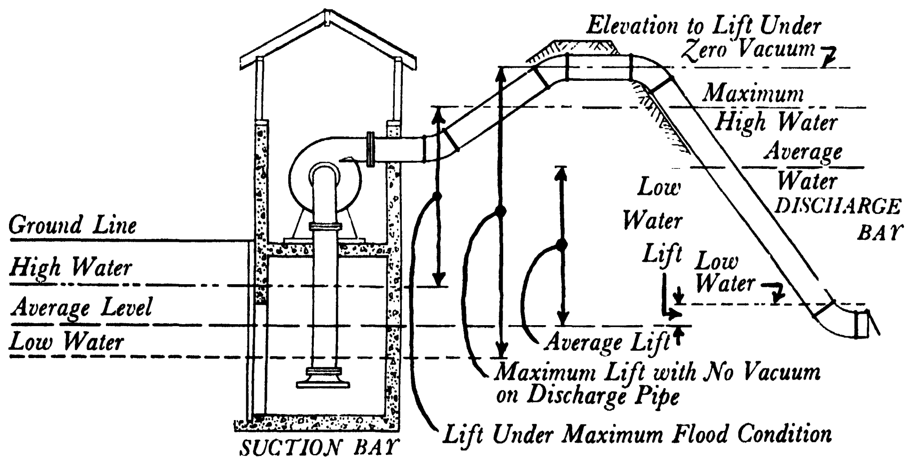
ROBERT M. SALTER *was chief of the Soil and Water Conservation Research Branch before his death Sept. 13, 1955. He was in charge of the research of the Agricultural Research Service in soil and water management, watershed hydrology, basic work in soil and plant relationships, and fertilizer technology. Before he assumed that position in 1953, he was chief of the Soil Conservation Service and chief of the Bureau of Plant Industry, Soils, and Agricultural Engineering.*

OMER J. KELLEY, *as head of the Western Soil and Water Management Section, Agricultural Research Service, supervises research on soil and water management and conservation practices in the 17 Western States. He received his doctor's degree in soil physics from the Ohio State University in 1942. He became project leader of soils work on the guayule research project. Later he was in charge of the soil and water management research program in the West.*

Appendix

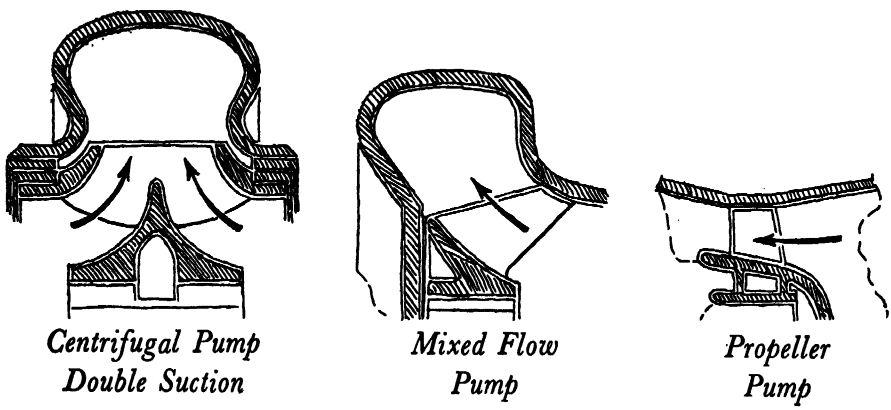


Plan of Suction Bay and Foundations

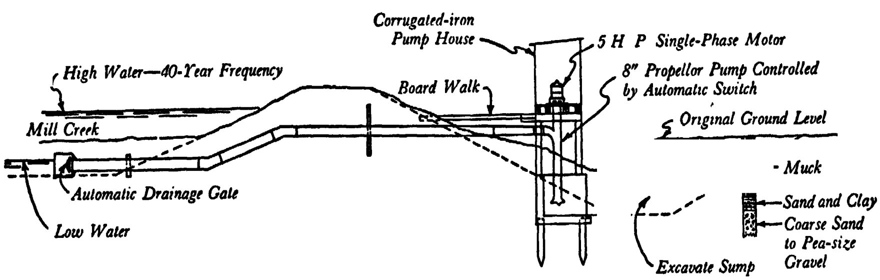


Elevation of Well-designed Pumping Plant

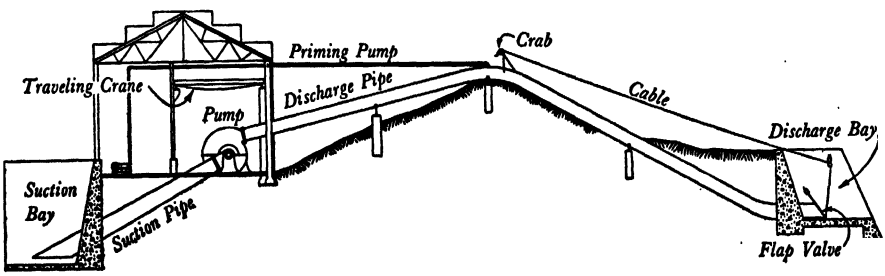
(See pages 528–538.)



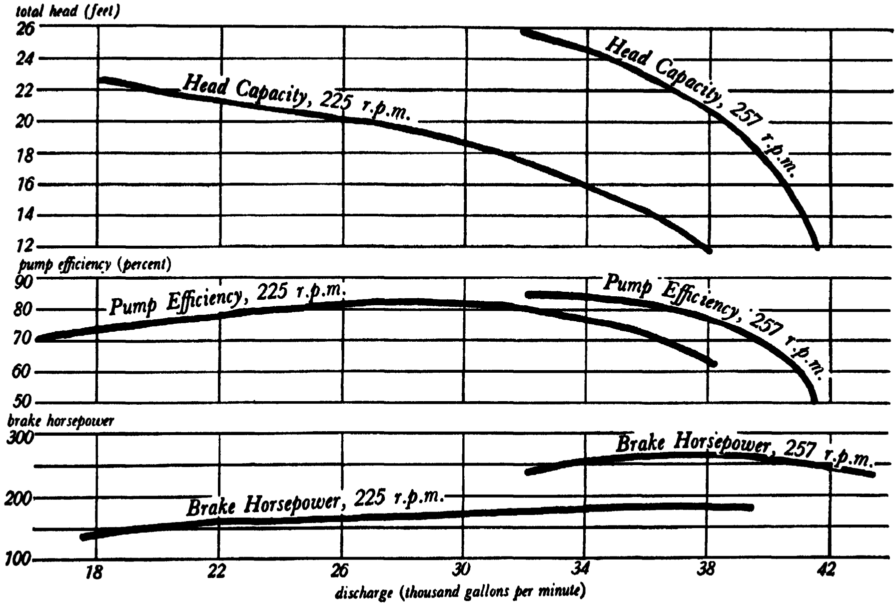
Sketch showing action of pump impellers used for drainage. (See pages 528–538.)



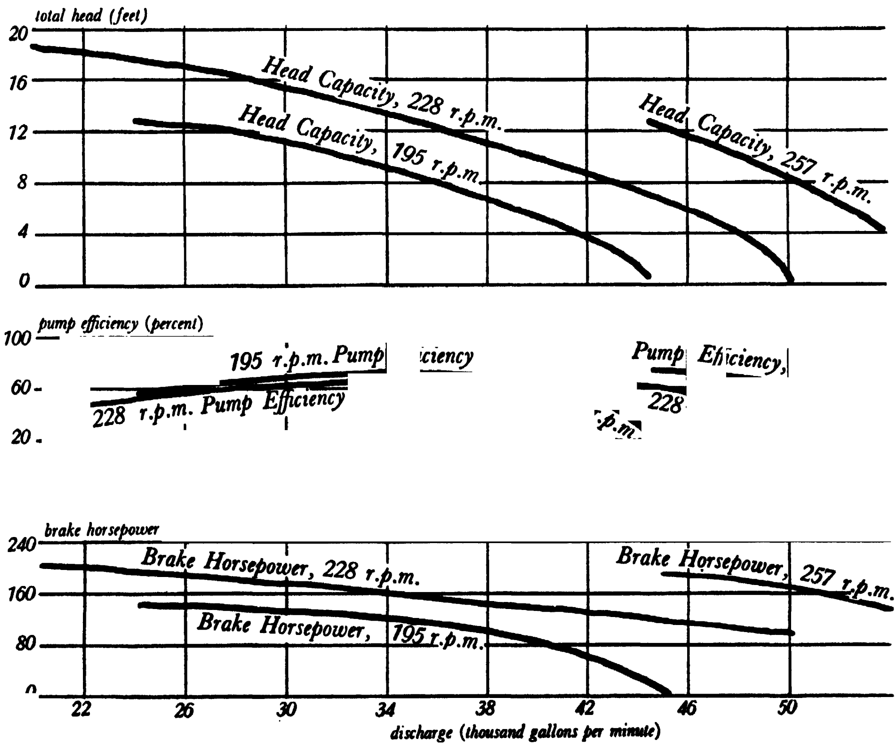
Elevation of well-designed farm pumping plant; Central Lapeer Soil Conservation District, Michigan. (See pages 528–538.)



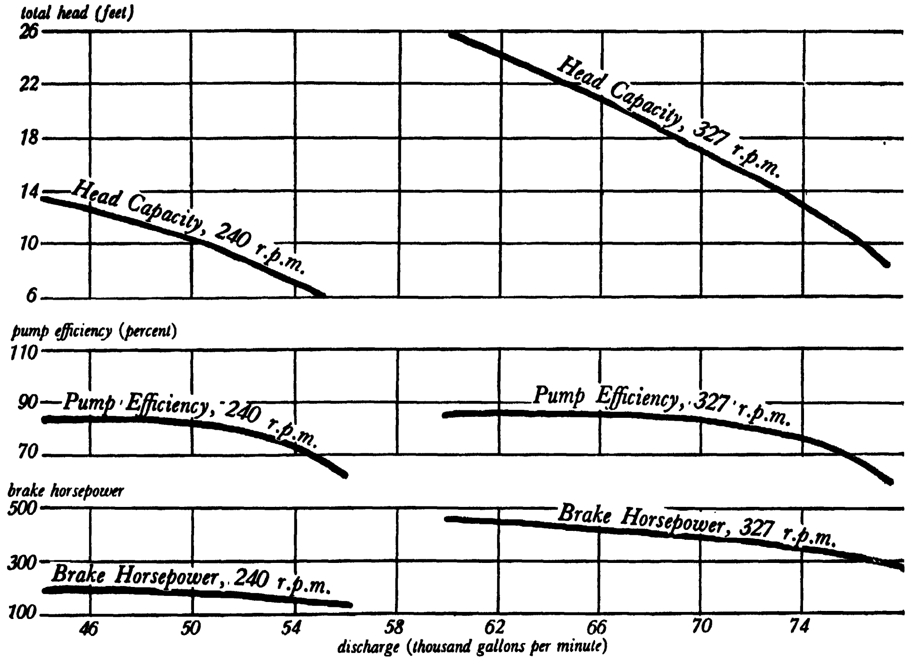
Elevation of well-designed pumping plant; reinforced suction and discharge bays (piling not shown; inclined suction pipe; discharge pipe over top of levee with long radius bends; crab for lifting flap gate. (See pages 528–538.)



Characteristic curves of centrifugal pump; field tests of 36-inch pump; Adams County, Ill. (See pages 528–538.)

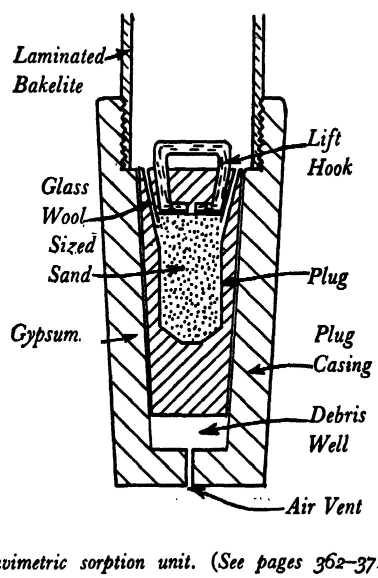


Characteristic curve for propeller type "screw" pump. (See pages 528–538.)

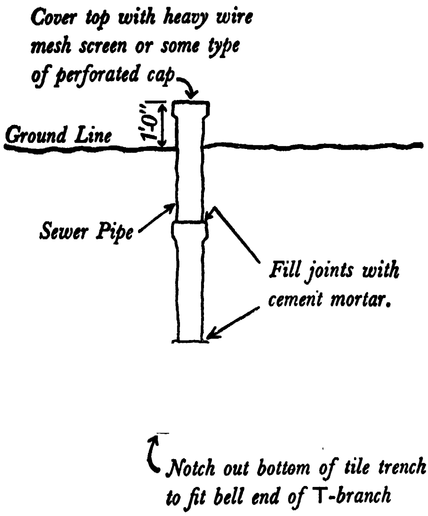


Characteristic curves of mixed-flow pump; field tests 48-inch pump; Green County, Ill. (See pages 528–538.)

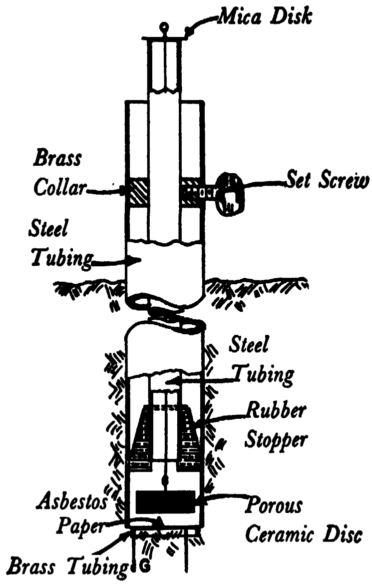
Tile junction using Y *and* T *connections. (See pages 508–520.)*



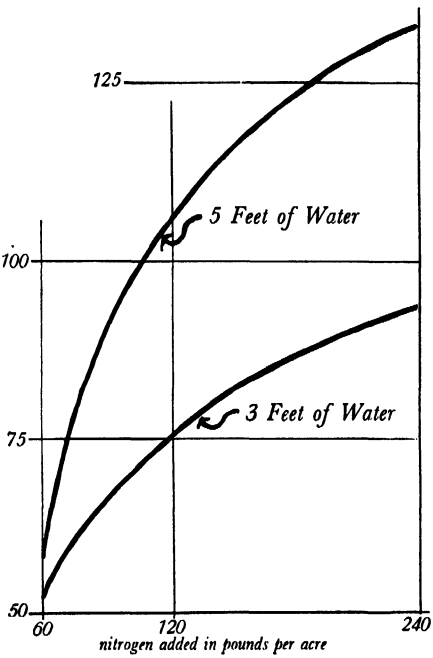
Gravimetric sorption unit. (See pages 362–371.)



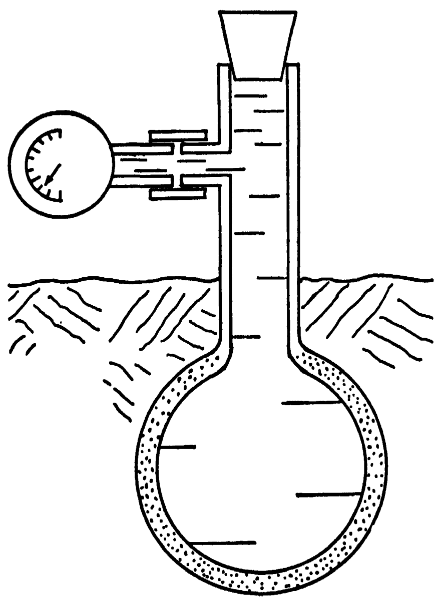
Breather or air vent. Can be used as a relief well by increasing size of the riser pipe. (See pages 508–520.)



Sorption block soil moisture meter. (See pages 362–371.)



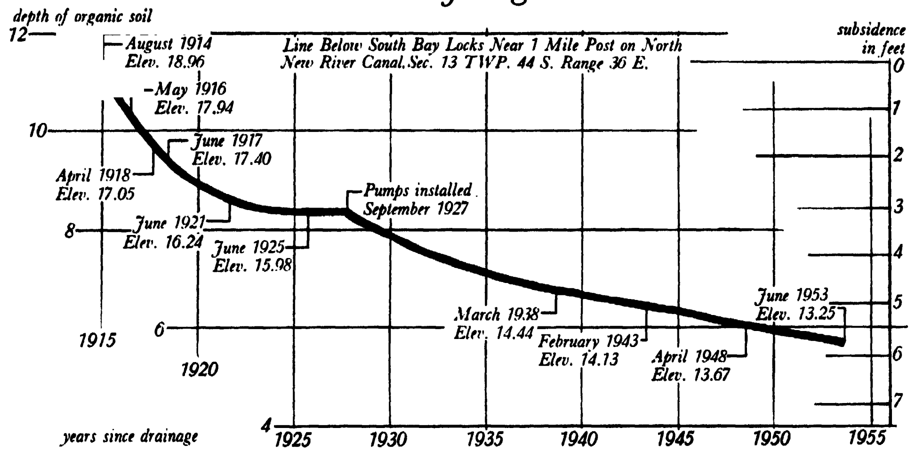
Result of an experiment showing how the value of additional nitrogen fertilizer was increased by supplying the plants with additional water. (See page 691.)



Soil-moisture tensiometer. (See pages 362–371.)

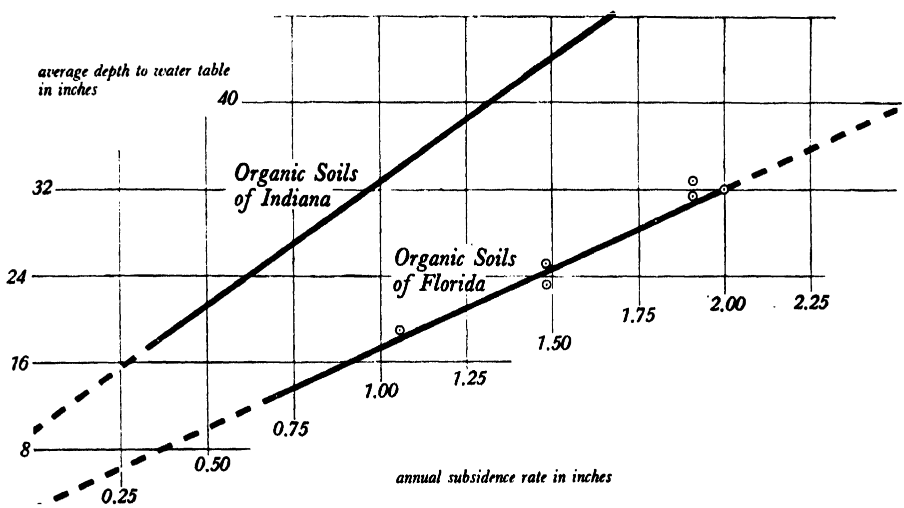
325862°—55——46

Subsidence of Organic Soils



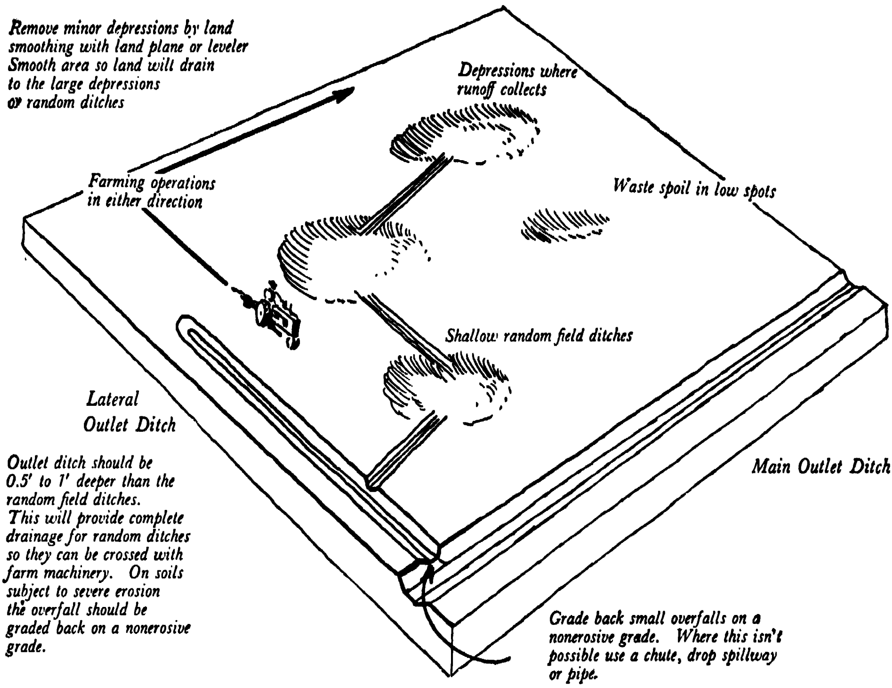
The subsidence rate of a drained organic soil over a period of nearly 40 years. The normal pattern of fast sinking of the surface with initial drainage, a leveling off as gravity drainage decreased, an increase in rate with better drainage due to pumping, and the steady loss of surface elevation thereafter are illustrated. Soil is Okeelanta peaty muck near South Bay, Florida. (See pages 539–557.)

Comparative Subsidence Rates in Organic Soils of the Northern and Southern United States



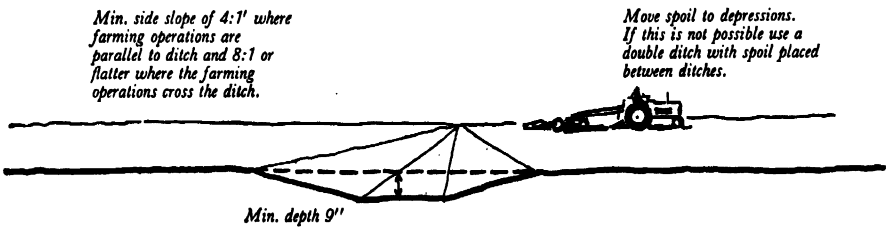
This shows that the subsidence rate for organic soils depends on the depth to the water table. The lower the water table, the greater the soil loss. Data from Indiana based on drainage depth during crop year, May to September only. For Florida, drainage depth was held the whole year. (See pages 539–557.)

Random Ditch System of Surface Drainage



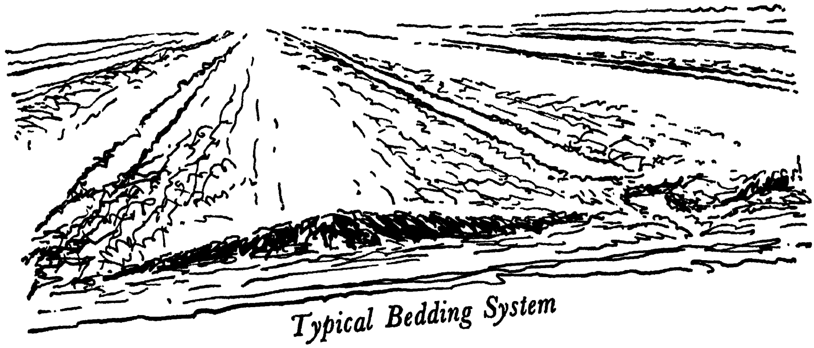
Cross Section of Random Ditch

Cross-sectional area should be designed for not less than applicable drainage runoff and never less than 5 sq. ft.

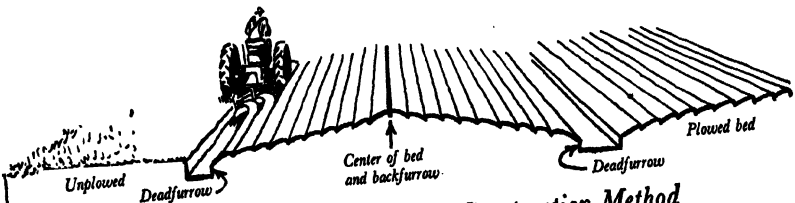


(*See pages 499–507.*)

The Bedding System of Surface Drainage

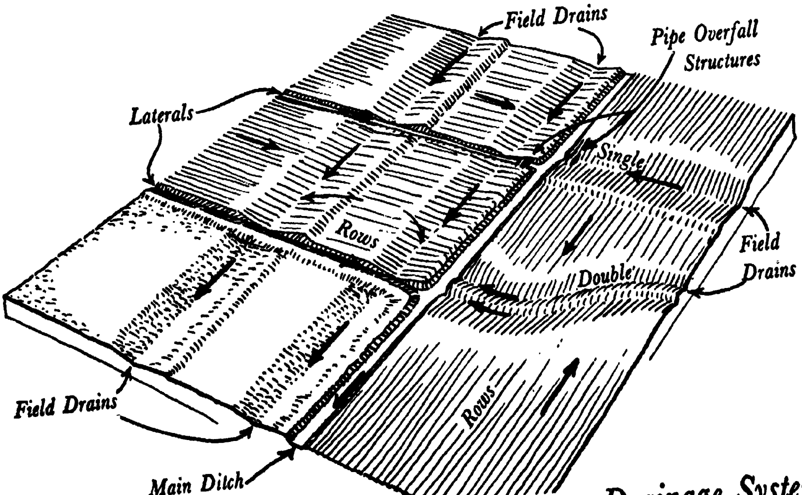


Typical Bedding System



Cross Section of Bed Showing Construction Method

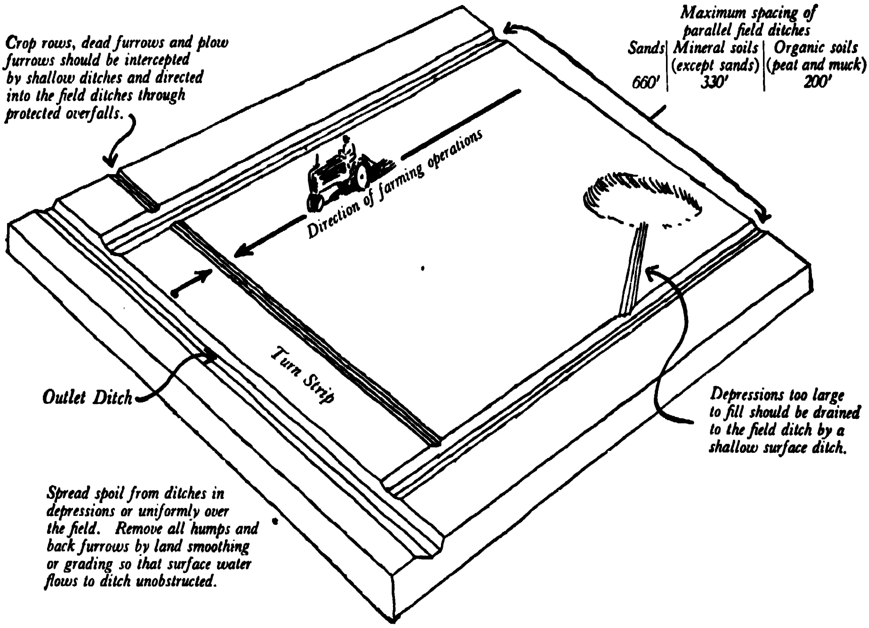
(See page 502.)



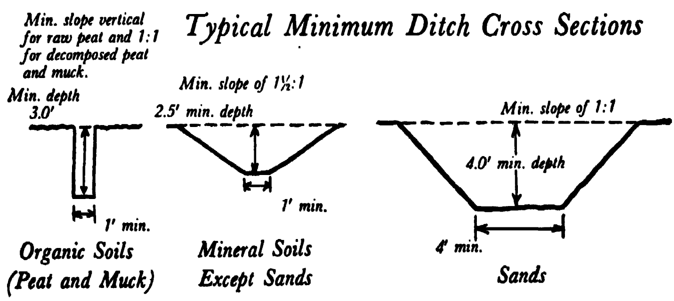
Individual Farm Drainage System

(See pages 499–507.)

Field Ditch System for Water Table Control and Surface Water Removal

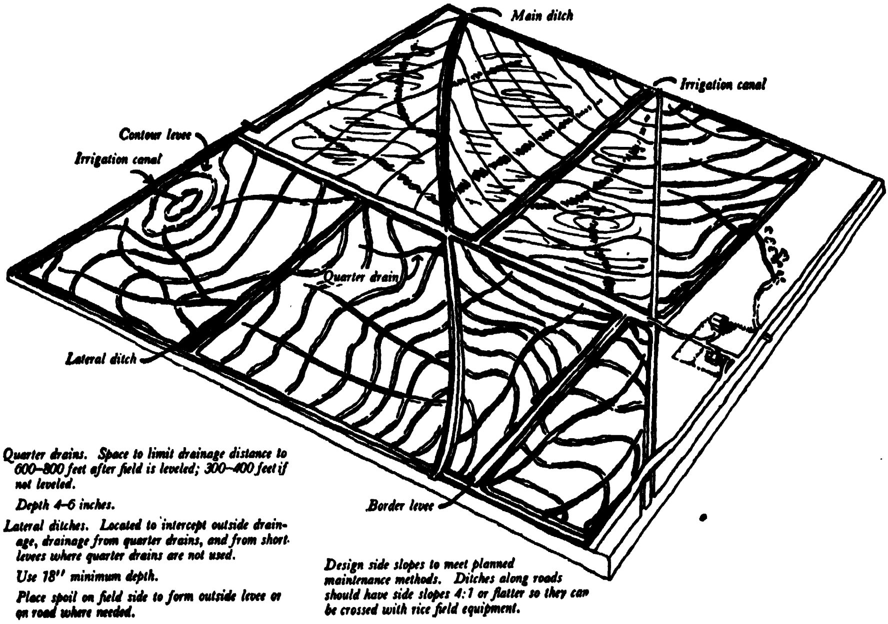


Typical Minimum Ditch Cross Sections

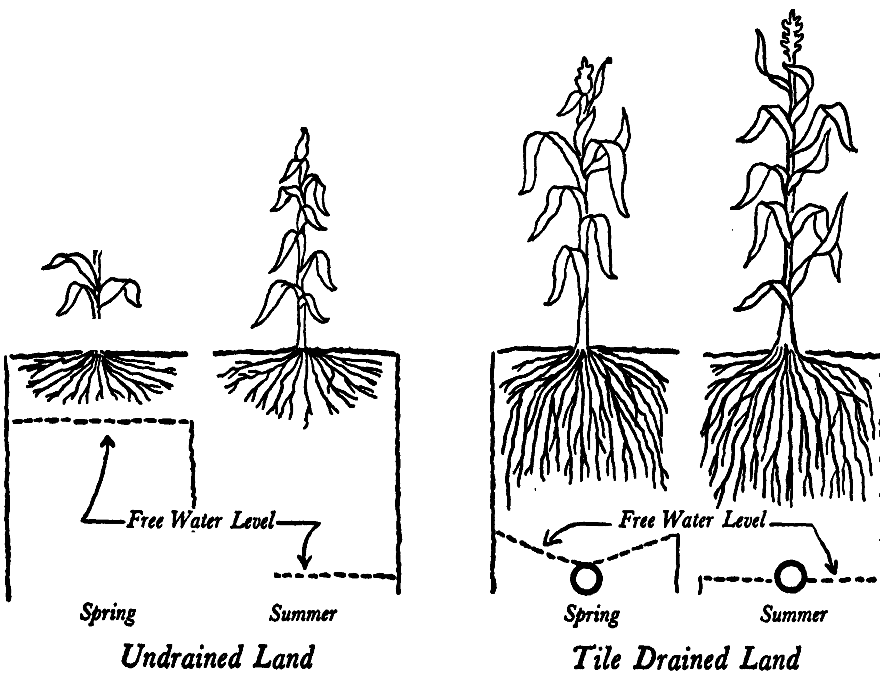


(*See pages 499–507.*)

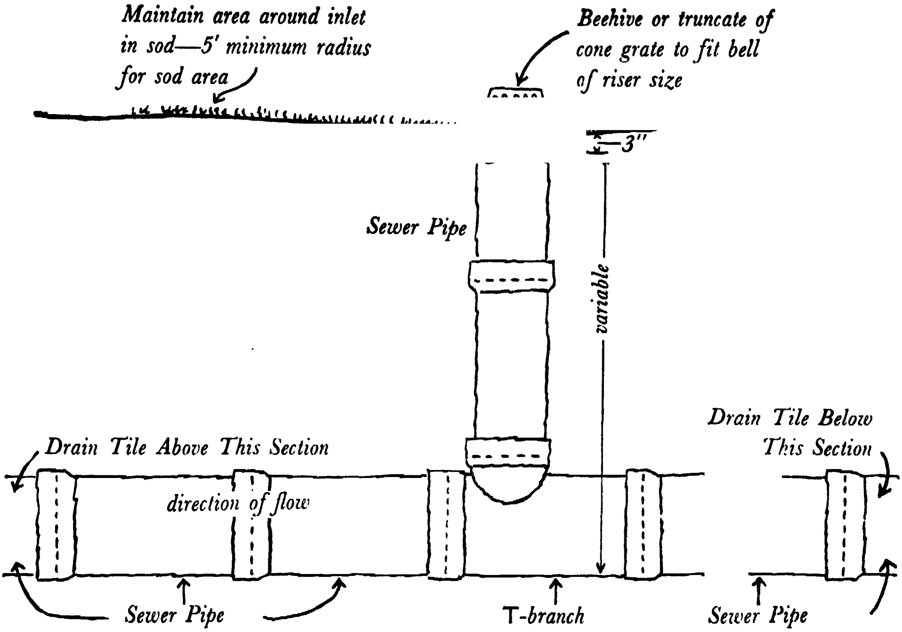
Individual Rice Farm Irrigation and Drainage System



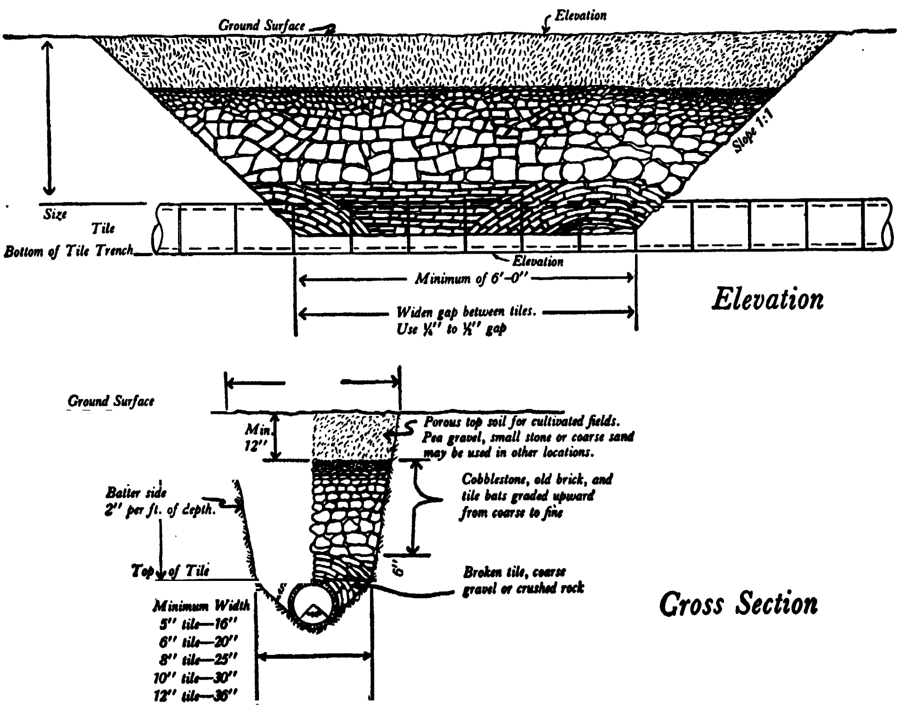
(*See page 503.*)



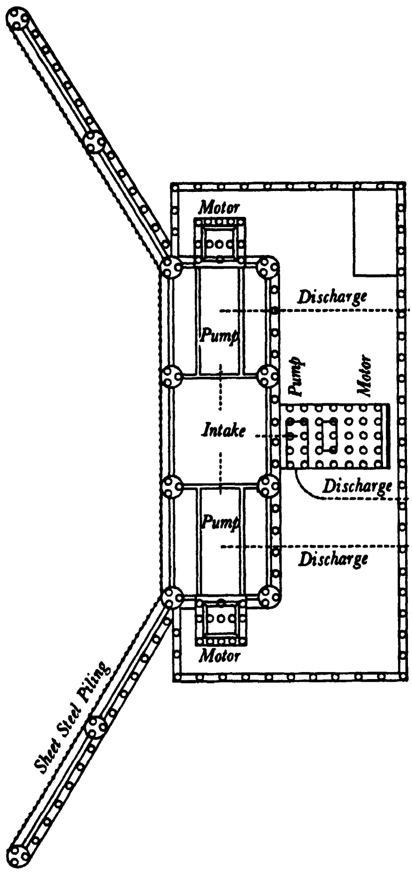
Root development of crops grown on tile drained and undrained land. (Redrawn from Manson and Rost: Agricultural Engineering 32: 6, 1951). (See pages 491–498.)



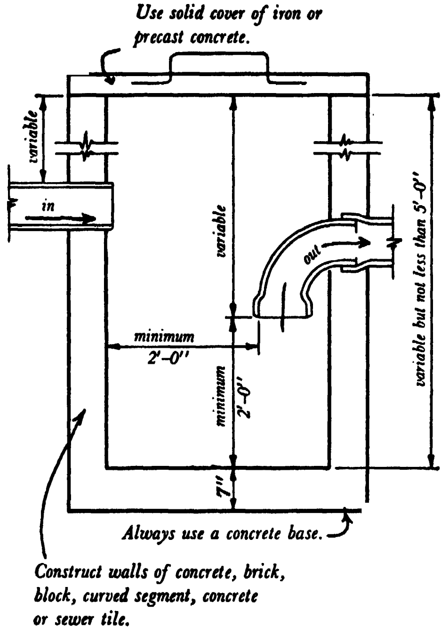
A small surface inlet made of sewer pipe for use on lateral tile lines. (See pages 508–520.)



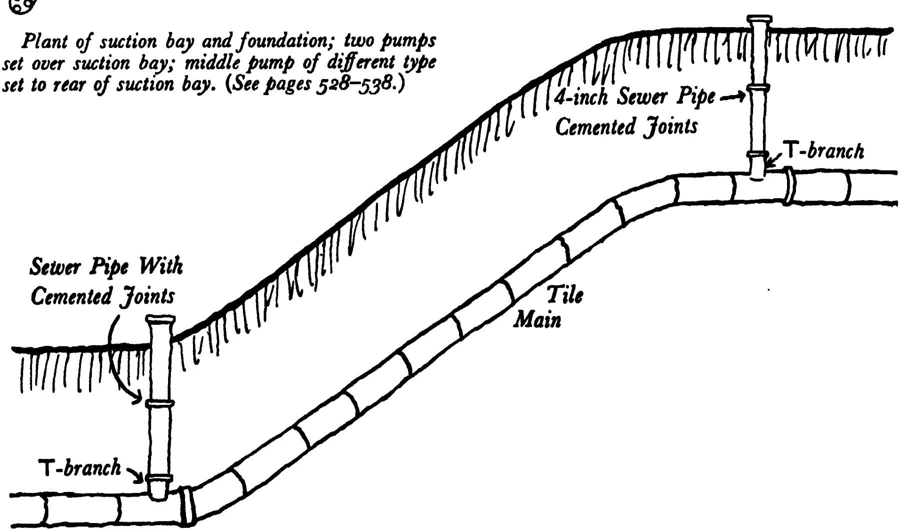
Sketch showing method of constructing blind surface inlet. (See pages 508–520.)



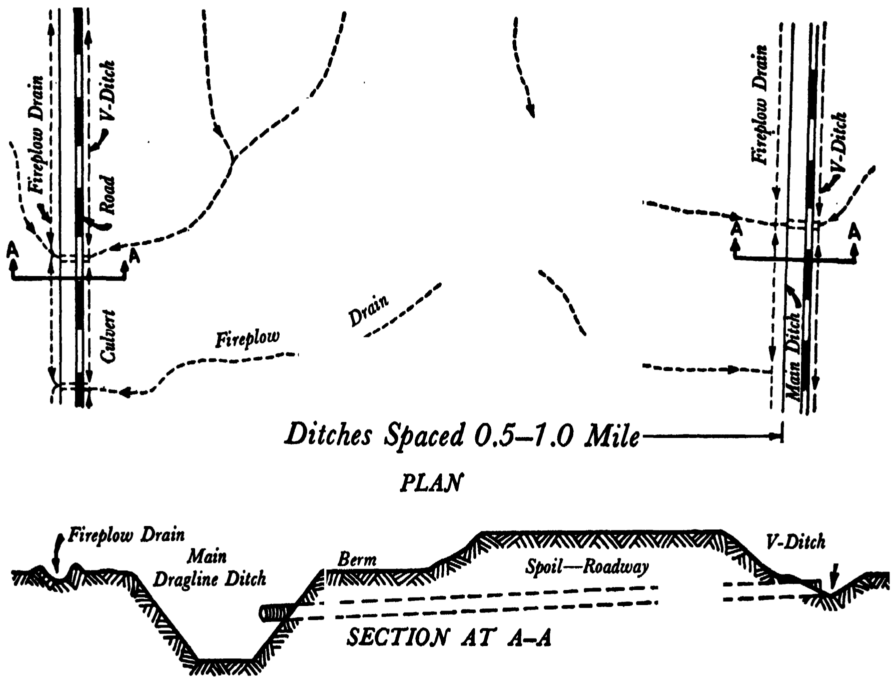
Plant of suction bay and foundation; two pumps set over suction bay; middle pump of different type set to rear of suction bay. (See pages 528–538.)



Typical sediment trap. (See pages 508–520.)



A drawing showing the placement of a breather near the beginning of a steep grade and a relief well at the end. (See pages 508–520.)



A plan and section of a drainage system in very flat, wet woodland. (*See pages 564–568.*)

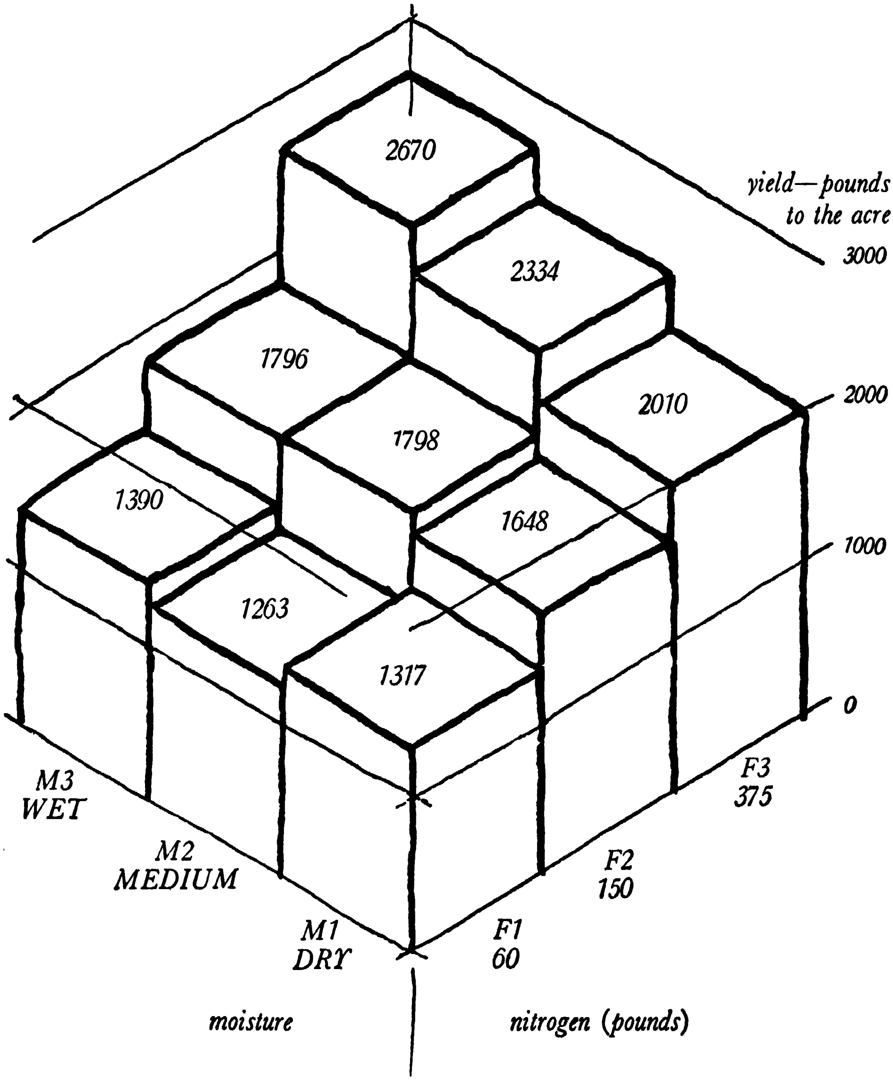
Adaptation and Limitations for Common Irrigation Methods

Furrow	Light, medium- and fine-textured soils; row crops; small stream.	Slopes up to 3 percent in direction of irrigation; row crops; 10 percent cross slope.
Corrugation	Light, medium, and fine-textured soils; close growing field crops; small stream flows.	Slopes up to 12 percent with semi-permanent crops; 8 percent with annual crops; 5 percent cross slope; rough for equipment.
Border	All soils; close growing field crops; large streams.	Slopes up to 3 percent for annual crops; slopes to 8 percent for sodded pastures; good leveling required; 0.3 percent cross slope; uniform grade; problem of starting crops in soils which puddle readily.
Sprinklers	All slopes; soils; crops; and stream size.	High initial equipment cost; lowered efficiency in windy and hot climate.
Check (or ponding)	Light, medium, and heavy soils; large streams.	Deep soils; high cost of land preparation; slopes less than 2 percent.
Subirrigation	Free lateral movement of water in soils, rapid capillary rise, underlain by low permeability layer; all crops; large quantities of water.	Special soil and annual precipitation conditions; usually causes drainage problems elsewhere.

(*Prepared by Max Jensen and Claude H. Pair*)

Factors Useful in Preliminary Planning of Smaller Pumping Plants

Pump or pipe size, in.	*Gallons per minute*	*Acres, inches per 24 hours*	*Pipe velocity, feet per second*	*Velocity head, $\frac{V^2}{2g}$ feet*	*Friction in feet per 100 feet of pipe*	*Horsepower required for 10 feet total head. Pump and transmission efficiency=70 percent*
6	400	21.2	4.54	0.32	2.21	1.4
6	600	31.8	6.72	0.70	4.7	2.2
6	800	42.4	9.08	1.28	8.0	
6	1,000	53.0	11.32	1.99	12.0	
8	900	47.7	5.75	0.52	2.46	3.2
8	100	58.3	7.03	.77	3.51	4.0
8	300	68.9	8.32	1.07	4.72	4.7
8	500	79.5	9.60	1.43	6.27	5.4
10	1,200	63.6	4.91	.38	1.46	4.3
10	1,600	84.8	6.56	.67	2.35	5.8
10	2,000	106.1	8.10	1.02	3.65	7.2
10	2,400	127.3	9.73	1.5	5.04	8.7
12	2,000	106.1	5.60	.48	1.43	7.2
12	2,500	132.6	7.00	.77	2.28	9.0
12	3,000	159.1	8.40	1.10	3.15	10.8
12	3,500	185.6	9.80	1.49	4.10	12.6
14	2,000	106.1	4.20	.27	0.66	7.2
14	3,000	159.1	6.30	.61	1.47	10.8
14	4,000	212.1	8.40	1.09	2.47	14.4
14	5,000	265.2	10.50	1.71	3.92	18.0
16	3,600	190.9	5.74	.51	1.10	13.0
16	4,400	233.3	7.01	.76	1.58	15.9
16	5,200	275.8	8.29	1.06	2.16	18.8
16	6,000	318.2	9.56	1.42	2.60	21.6
18	4,500	238.6	5.70	.50	0.93	16.2
18	5,500	291.7	6.96	.75	1.32	19.8
18	6,500	344.7	8.22	1.05	1.82	23.4
18	8,000	424.2	10.02	1.56	2.65	28.9
20	5,000	265.2	5.13	.41	0.68	18.0
20	6,500	344.7	6.66	.69	1.06	23.4
20	8,000	424.2	8.17	1.03	1.63	28.9
20	10,000	530.3	10.40	1.68	2.53	36.1
24	8,000	424.2	5.68	.50	0.66	28.9
24	10,000	530.3	7.07	.78	0.98	36.1
24	12,000	636.4	8.50	1.12	1.40	43.3
24	14,000	742.4	9.95	1.54	1.87	50.5
30	12,000	636.4	5.44	0.46	0.47	43.3
30	16,000	848.5	7.36	.84	0.83	57.7
30	20,000	1061.0	9.09	1.29	1.22	72.2
30	24,000	1273.0	10.90	1.86	1.71	86.6



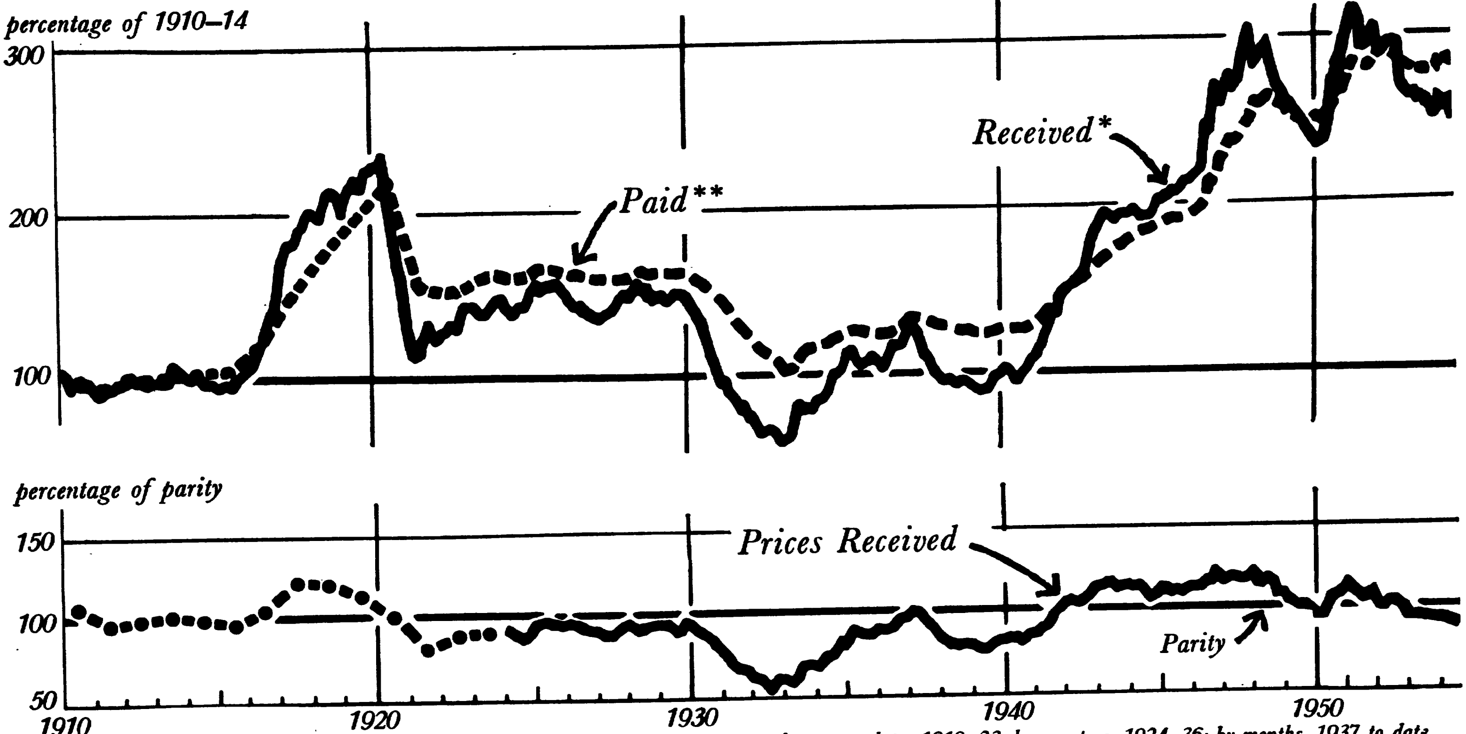
The effect of moisture and nitrogen on the yield of seed cotton, Yuma, Ariz., 1952. (See pages 381-388.)

Wet—Irrigated when the root zone soil moisture tension reached 0.2 atmospheres.

Medium—Irrigated when the root zone soil moisture tension reached 0.6 atmospheres.

Dry—Irrigated when the root zone soil moisture tension reached 9 atmospheres.

Farmers' Prices



*Monthly data **Includes interest, taxes, and wage rates. Annual average data, 1910–23; by quarters, 1924–36; by months, 1937 to date.

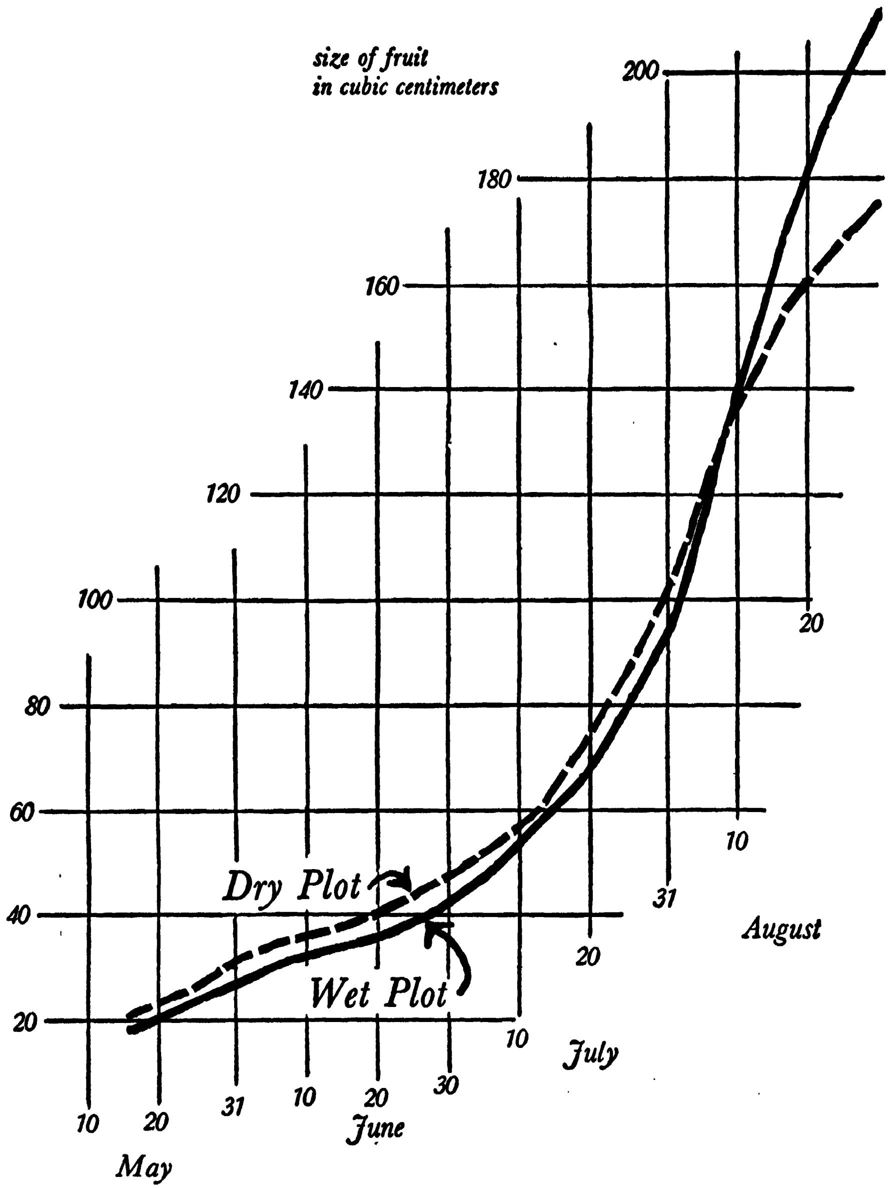
This drawing shows farmers' prices received and paid in the years 1910–1954. Prices received by farmers for farm products have varied much more than prices paid for things used in farm production. In agriculture, prices received have had a wider range with less change in production than in industry. During and immediately after both World Wars, farm product prices rose more than wholesale prices of manufactured goods. The weakening demand following each war was reflected in rather sharp declines in prices of agricultural products, with little or no reduction in output, but with considerable decreases in farm incomes. With the drop in incomes, less was available for land improvement. (See pages 479–491.)

Group-Enterprise Plans in Soil Conservation Districts, United States Totals, Fiscal Year 1954, and Cumulative to June 30, 1954 [1]

Item	Group drainage		Group irrigation		Other types [2]		Total	
	1954	Cumulative	1954	Cumulative	1954	Cumulative	1954	Cumulative
Group job plans.........number..	1, 343	11, 554	341	2, 463	23	248	1, 707	14, 265
Farms to be benefited....number..	7, 023	78, 127	8, 490	48, 365	212	2, 680	15, 725	129, 172
Areas to be benefited.......acres..	649, 405	7, 793, 910	533, 917	2, 646, 320	17, 236	508, 609	1, 200, 558	10, 948, 839
Estimated cost...........dollars..	4, 203, 621	40, 685, 603	2, 059, 413	13, 456, 105	89, 313	2, 473, 897	6, 352, 347	56, 615, 605
Group jobs completed....number..	1, 111	9, 113	304	1, 899	14	181	1, 429	11, 193
Farms benefited.........number..	5, 771	52, 449	8, 409	38, 226	84	1, 832	14, 264	92, 507
Area benefited............acres..	469, 974	4, 871, 275	359, 231	1, 847, 751	5, 009	277, 176	834, 214	6, 996, 202
Some principal practices installed:								
Ditch and canal excavation miles..	1, 134	10, 999	176	1, 713	14	107	1, 324	12, 819
Do.........cubic yards..	10, 441, 200	98, 957, 364	795, 318	5, 977, 296	103, 752	3, 533, 299	11, 340, 270	108, 467, 959
Spoil-bank leveling cubic yards..	4, 914, 318	48, 456, 802	41, 582	407, 587	10, 692	1, 020, 985	4, 966, 592	49, 885, 376
Levees and dikes.......miles..	14	266	4	53	5	52	23	371
Do.........cubic yards..	197, 411	3, 376, 754	132, 677	883, 642	79, 945	972, 780	410, 033	5, 233, 176
Channel stabilization...miles..	10	235	2	60	1	35	13	330
Drainage and irrigation pipe lin. feet..	901, 069	3, 733, 064	64, 012	338, 872	10	3, 504	965, 091	4, 075, 440
Reservoirs..........number..	3	9	14	142	3	19	20	170
Do...........acre-feet..	498	1, 044	9, 506	70, 828	44	593	10, 048	72, 465
Structures..........number..	1, 062	9, 565	1, 011	8, 002	3	157	2, 076	17, 724

[1] A group-enterprise plan is defined as any job involving two or more landowners or operators who agree to work together to carry on the construction operations, and maintenance specified in the plan.

[2] Other types include special erosion control, water control, water spreading, and other such group-enterprise jobs.



Peaches that show the effect of the lack of readily available moisture early in August.
(See pages 456–461.)

General Relationships Between Soil Moisture and the Feel and Appearance of the Soil

Moisture between wilting point and field capacity	Feel or appearance			
	Coarse soil	Light soil	Medium soil	Heavy and very heavy soil
0	Dry, loose, single-grained, flows through fingers	Dry, loose, flows through fingers	Dry, sometimes slightly crusted but easily breaks down to powdery condition	Hard, baked, cracked, sometimes has loose crumbs on surface
50 percent or less	Appears dry, will not form ball with pressure	Appears dry, will not form ball [1]	Somewhat crumbly, holds together from pressure.	Somewhat pliable, balls under pressure
50 to 75 percent	Same as coarse under 50 percent or less	Tends to ball under pressure but seldom holds together	Forms ball, somewhat plastic, will sometimes slick slightly with pressure	Forms ball, ribbons out between thumb and forefinger
75 percent to field capacity	Tends to stick together, sometimes forms very weak ball under pressure	Forms weak ball, breaks easily, will not slick	Forms ball, very pliable, slicks readily if high in clay	Easily ribbons out between fingers, has slick feeling
At field capacity	Wet outline of ball is left on hand upon squeezing	Same as coarse	Same as coarse	Same as coarse
Above field capacity	Free water appears when soil is bounced in hand	Free water released with kneading	Can squeeze out free water	Puddles and free water forms on surface

[1] Ball is formed by squeezing a handful of soil very firmly.

(Prepared by Max Jensen and Claude H. Pair)

Runoff for National Forest and Non-National Forest Areas in Certain Western Drainage Basins

Drainage basin or area	Area: NF, percent	Area: Outside NF, percent	Average annual water production: Whole area, inches	NF: Inches	NF: Percent of total volume	Outside NF: Inches	Outside NF: Percent of total volume
Columbia (in U. S.)	37	63	10.4	16.7	59	6.7	41
Colorado (in U. S.)	19	81	2.5	7.2	56	1.3	44
Rio Grande above El Paso	25	75	1.7	3.8	58	0.9	42
Central Valley (California only)	32	68	11.8	23.5	63	6.4	37
Rogue-Umpqua Area	40	60	35.5	37.0	42	34.2	58
Northwest Washington (State less Columbia)	32	68	39.3	51.4	41	33.7	59
Southern California Coast (Los Angeles watershed to Mexican border)	25	75	3.7	6.3	43	2.8	57
North Platte and South Platte	11	89	1.7	6.2	41	1.2	59
Missouri above Fort Randall Dam [1]	9	91	1.7	6.9	37	1.2	63
Arkansas above Dodge City [2]	9	91	1.2	4.7	38	0.7	62

[1] Ft. Randall Dam is in South Dakota and close to the Nebraska line.
[2] Dodge City, Kans., is close to the 100th Meridian.

Precipitation and Runoff for National Forest and Non-National Forest Areas in the 11 Western States

State	Area: NF, percent	Area: Outside NF, percent	Average annual precipitation: Whole State, inches	NF: Inches	NF: Percent of total volume	Outside NF: Inches	Outside NF: Percent of total volume	Average water production: Whole State, inches	NF: Inches	NF: Percent of total volume	Outside NF: Inches	Outside NF: Percent of total volume
Ariz.	16	84	12.0	18.4	25	10.7	75	0.7	1.5	37	0.5	63
Calif.	25	75	21	34	41	17	59	8.6	19.2	57	5.0	43
Colo.	23	77	16	20	28	15	72	4.4	11.4	61	2.2	39
Idaho	40	60	18	24	53	14	47	8	15	70	4	30
Mont.	21	79	15	18	25	14	75	4.4	12.2	58	2.4	42
Nev.	8	92	8.1	9.7	9	8.0	91	0.5	1.1	16	0.5	84
N. Mex.	13	87	14.4	16.6	15	14.0	85	0.6	1.7	36	0.5	64
Oreg.	29	71	28	39	39	24	61	14	22	44	11	56
Utah	17	83	10.8	15.7	25	9.7	75	2.0	6.5+	57	1.0	43
Wash.	26	74	39	59	38	32	62	18	31	45	13	55
Wyo.	15	85	14	18	19	13	81	4.1	14.7	54	2.2	46
Mean	21	79	17	26	32	15	68	5.5	14.0	53	3.3	47

Source of data: Annual Runoff in the United States, Walter B. Langbein and others, Geological Survey Circ. 52, 1949. Prepared in the Division of Watershed Management Research, Forest Service, 1952.

Convenient Equivalents for Planning and Testing Pumping Plants

VOLUME

1 U. S. gallon=231 cubic inches=0.13368 cubic foot.

1 cubic foot=1,728 cubic inches=7.4805 U. S. gallons.

1 acre foot=325,851 U. S. gallons=43,560 cubic feet.

HYDRAULICS

1 U. S. gallon of water weighs 8.34 pounds.

1 cubic foot of water weighs 62.4 pounds at 4° C.

1 cubic foot per second=448.83 gallons per minute=646,317 U. S. gallons per day=0.9917 acre inch per hour (usually taken as unity)=1.9835 acre feet per 24-hour day (usually taken as 2).

1 million gallons per day=1.5472 C.F.S.=3.07 acre-feet per day.

1 inch runoff per 24 hours=26.889 cubic feet per second per sq. mi.=0.0420 cubic feet per second per acre=18.857 gallons per minute per acre.

1 inch per hour=1.0083 cubic feet per second per acre (usually taken as unity).

PRESSURE

1 foot of water at 39.1° F.=62.425 lbs. per sq. ft.=0.4335 lbs. per sq. inch=0.8826 inch of mercury at 30° F.

1 atmosphere at sea level=33.90 feet of water.

1 pound on the sq. inch at 39.1° F.=2.307 ft. of water.

1 inch of mercury at 32° F.=1.133 feet of water=0.49119 lb. per sq. inch.

MISCELLANEOUS

1 year=8,760 hours.

1 second-foot falling 8.81 feet=1 horsepower.

Acceleration of gravity g=32.16 ft. per second per second.

1 horsepower=550 foot pounds per second=33,000 foot pounds per minute=746 watts.

1 kilowatt=1,341 horsepower.

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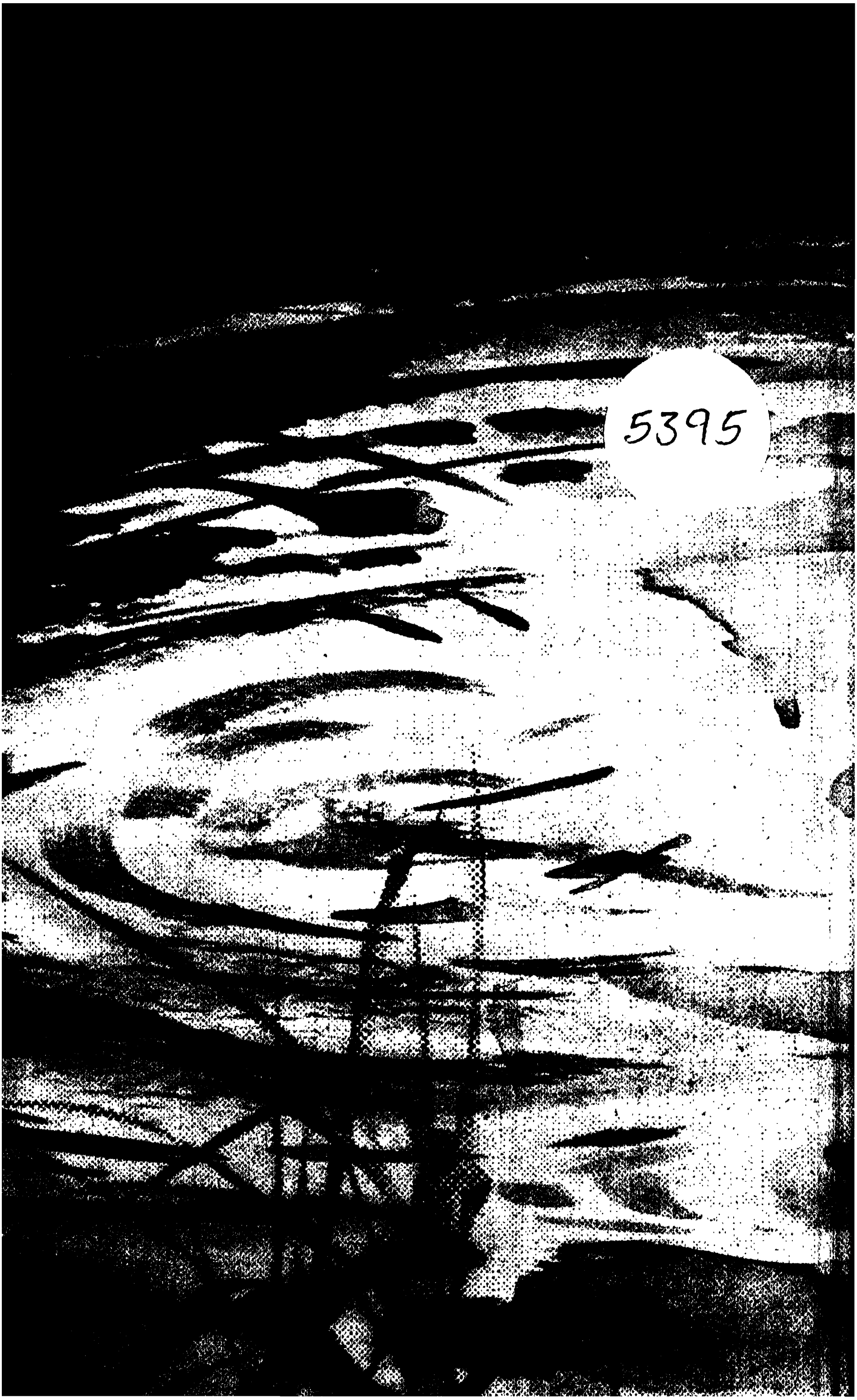
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